A PARAMETRIC STUDY OF FLOOD ROUTING THROUGH A RIVER

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By

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CERTIFICATE

The thesis 'A PARAMETRIC STUDY OF FLOOD ROUTING
THROUGH A RIVER' by Vinay Kumar is hereby approved
as a creditable report on research carried out and
presented in a manner which warrants its acceptance as a
prerequisite for the degree of MASTER OF TECHNOLOGY.
The work has been carried out under my supervision and
has not been submitted else-where for a degree.

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SYNOPSIS

A knowledge of the way in which a flood wave
attenuates as it travels downstream along a long open
channel with a continuously moving unsteady- steady
boundary is of importance in flood routing.

Implicit scheme was used and a dimensional
analysis was carried out to consider all the significant
parameters that affect the flood propagation. A systematic
analysis was made by varying all the parameters in the
practically possible range.

It was found that relative flood wave amplitude
depends upon initial wave amplitude ratio of time to peak
to time to centre of gravity of the inflow hydrograph,
and Manning's n. The first two terms take into account
the rate of rise of hydrograph, time of travel of the
wave peak is chiefly dependent upon initial wave amplitude.
These conclusions are very important in prediction of the
peak stage and time of its occurrence.

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LIST OF SYMBOLS

A = Area

C = Intercept on ordinate on XY plane

C_o = Celerity of wave $= \sqrt{g \times \text{depth of flow}}$

g = Gravitational Constant

m = Slope of the time on XY plane

n = Manning's roughness

q_o = Steady flow discharge

Q_* = Relative discharge rise

t_p = time to peak of the inflow hydrograph

t_g = time to centre of gravity of the inflow hydrograph

T_p = Time to peak since starting of the hydrograph

T_* = Dimensionless time to peak

V_o = Initial steady state velocity

X = Dimensionless distance $= \dfrac{x}{y_o}$

x = Distance along the channel

y_o = Steady flow depth

y_w = Wave amplitude

Y_w = Dimensionless wave amplitude $= \dfrac{y_w}{y_o}$

Y^+ = $1 - Y_*$

Y_* = Relative wave amplitude

LIST OF FITURES

CHAPTER I

INTRODUCTION

Our civilization has grown on the banks of rivers
and for hundreds of years they were and are still a
boon to mankind. But with the development of science,
man tried to bind these rivers to flow on a particular
path, wanted to cross them through strong bridges and
thus to a great extent disturbed their natural flow.
Some times dams are constructed, water is regulated in
a particular way and thus taking the control in one's
hand. One of the most important of all the unsteady
flow phenomena the engineer has to deal with, is the
movement of a flood wave down a channel, usually in
the case of a river, and the problem along with this
is the tracing of this movement and any related changes
in the form and height of the wave. It is necessary
that the engineer should possess theoretical or
accurate semi-empirical means of determining the
behaviour of a flood wave in a channel of specified
form and slope, so that he may be able to predict
the effect of the changes which he often makes in a
channel in the interests of channel improvement and
flood control.

Flood routing is the process of tracing by calculation the course of a flood wave and in large measure this problem is an application of the principles of unsteady flow. However a flood wave has its own features and may require its own special techniques for exploring these features. As for example, rise and fall of a flood occurs much more slowly than many of the flow changes in unsteady flow phenomena and so some of the acceleration terms in the equation of motion may not be of much significance, or otherwise, when the flood wave propagates, it becomes longer and lower as it moves downstream and this subsidence is very important for a practicising engineer. He may, therefore prefer instead of a general solution, an approach which concentrates on those aspects of the solution that are particularly relevant to the subsidence problem.

A semi-empirical method known as the Muskingum method, first developed by McCarthy [31] has been in use for many years. This method, which uses the equation of continuity and some empirical constants which characterise the basin concerned was presented by

Linsley [20]. This coefficient method is by no
means an exact method of routing hydrographs in as
much as only a few of terms of governing equations are
considered in the derivation. The method though adequate
for many purposes such as in the planning and designing
stages of flood control or multiple-purpose projects,
reduction in natural flows resulting from the control
of floods by reservoirs etc., is of limited utility as
it does not take into account the dynamics of flow.
In recent years the advancement of computer technology
has estimulated the development and application of
a more rigorous approach of the numerical integration
of the equations of motion and continuity for unsteady
flow. A great deal of effort has been made to develop
computational methods applicable to the routing of a
flood wave in a complex natural or hypothetical drainage
system. However, it is worth mentioning that the
significant factors influencing the unsteady flow
phenomena are so numerous and any typical watershed
is so complicated that it is very difficult to
arrive at any reliable conclusion.

The precise role of each factor affecting the flood wave propagation in open channels can best be understood by studying the flow in a relatively simple and ideal channel in which all important parameters can be independently and systematically varied. For example, the relations among important flood characteristics, such as maximum stage with Manning's roughness, initial wave amplitudes time to peak of the hydrograph, distance etc. may be studied. It may be also possible to arrive at a result which can be used to get an empirical formula and thus help in flood prediction.

An approach of this type in open channel was applied by Mozayaney and Song. But their work is of very restrictive nature as the wave amplitude and, the length of the channel are small.

The transient flows due to a +vely skewed hydrograph of given duration at the upstream end of long rectangular straight channel were computed by implicit method. Implicit method was used because it is a very stable method and can be used very easily in

the case of natural rivers as shown by Amein in his
paper |4|. Though the stability of the scheme makes
its use convenient and easy for various dT and dx i.e.
time step and distance step, it will have some
numerical damping.

The inflow hydrograph taken was +vely skewed
one because most of the practical hydrographs resemble
this shape. Sine curve can also be used but then
it does not represent the actual field problem and
since the motive is to study subsidence with more
practical input data, log pearson type III hydrograph
was considered more useful. The initial wave emplitudes
were 0.5, 1 and 2 times the initial water depth,
the ratio of time to peak to the time to center of
gravity of the hydrograph was 1/3 and 2/3,
Manning's roughness coefficients were 0.02, 0.025, 0.03.
These parameters were used in different groups and
the resulting propagation of the flood wave was
calculated. The damping of the peak stage and the
time of occurrence of peak were studied in detail
which will be presented in this report.

CHAPTER II

2.1 Assumptions

The one dimensional equations of continuity
and momentum of unsteady flow in open channels are
referred to as St. Venant's equations.   These equations
are derived in any standard text book on unsteady flow
e.g. Mahmood and Yevjevich, Chow, Henderson etc.   The
following are important assumptions in the derivation
of these equations.

(1)   The channel is straight and uniform in the
       reach so that the one dimensional approach can
       be applied.

(2)   Velocity distribution across the wetted area
       does not substantially affect the wave propagation,

(3)   Friction losses are given by Manning's formula
       i.e. it is equal to loss in steady flow conditions.

(4)   The average slope of the channel bottom is
       small therefore $\tan \alpha = \sin \alpha$ and $\cos \alpha = 1$.

(5)   The wave surface varies gradually which is
       similar to stating that the pressure distribution
       is hydrostatic.

(6)   Flow is subcritical so the kinematic wave is important.

2.2 Equation of Continuity:

A short reach of channel of length Δx with the flow taking place from section 1-1 to section 2-2, shown in figure 2.2.1. Assuming x to represent the horizontal distance, ρ the density of water, g, the acceleration due to gravity, z the channel bottom elevation, y, the water depth, A the cross-sectional area; and v the average velocity. If Q be the volume flow rate entering the channel through section 1-1;

$Q + (\frac{\partial Q}{\partial x}) \Delta x$ will be the volume outflow rate; the mass f water entering the channel reach during Δt time will be $\rho \cdot Q \cdot \Delta t$.

The mass of water leaving the channel during the same time would be

$$\rho (Q + \frac{\partial Q}{\partial x} \Delta x) \cdot \Delta t.$$

Assuming Q to increase with x i.e. $\partial Q/\partial x$ is +ve there is a net mass outflow from the reach. Applying

law of mass conservation during time Δt, it can be easily concluded that mass inside the reach will be reduced and consequently the water surface should fall. The mass of water inside the reach of length Δx is

$$\rho A \; \Delta x.$$

The rate of decrease of this mass is

$$- \frac{\partial}{\partial t} (\rho A \Delta x) = - \rho \Delta x \frac{\partial A}{\partial t}$$

The reduction in mass during time interval t is

$$- \rho \Delta x \left(\frac{\partial A}{\partial t} \right) \Delta t$$

For the conservation of mass,

the net mass outflow = Reduction in mass inside the

$$\rho \left(Q + \frac{\partial Q}{\partial x} \Delta x \right) \Delta t - (\rho Q \Delta t) = - \rho \frac{\partial A}{\partial t} \Delta t \Delta x$$

which gives on simplification

$$\frac{\partial Q}{\partial x} = - \frac{\partial A}{\partial t}$$

Since Q = AV

$$V \frac{\partial A}{\partial x} + A \frac{\partial V}{\partial x} + \frac{\partial A}{\partial t} = 0 \qquad (1)$$

The momentum equation can be easily derived from the Newton's second law of motion which states that the time rate of change of momentum is equal to the external force applied, both being considered in the some direction.

Referring again to Fig. 2.1, the applied forces on the element are pressure force, gravity and frictional forces. If water depth is y at section 1-1, water depth at 2-2 will be $y + \frac{\partial y}{\partial x} \Delta x$ and similarly area at 1-1 is A, area at 2-2 is $A + \frac{\partial A}{\partial x} \Delta x$ assuming higher order terms f Taylor's series vanish or are negligibly small.

Pressure at section 1 - 1 acting to right $= \rho g \cdot y$

and the same at 2-2 acting to left,

$$= \rho g \left(y + \frac{\partial y}{\partial x} \Delta x \right)$$

net pressure force $= \rho gy - \rho g(y + \frac{\partial y}{\partial x} \Delta x)$

$$= - \rho g \frac{\partial y}{\partial x} \Delta x.$$

Unbalanced pressure force is

$$= - \rho \, gA \, \frac{\partial y}{\partial x} \, \Delta x$$

This will act towards the negative x-axis.

The component of the gravity force which is in the direction of motion is

$$= \rho \, gA \, \Delta x \qquad \frac{\Delta z}{\Delta x}$$

but $\frac{\Delta z}{\Delta x}$ = channel bottom slope So.

Therefore, the gravity force in the direction of motion is $\rho \, gA \, S_0 \, \Delta x$. The shear force opposes the motion and is directed toward the left.

Shear force can be expressed in terms of the head loss as follows,

$$\tau \, P \, \Delta x \; = \; \gamma \, h_L \, A$$

Where P is wetted perimeter and h_L is the head loss over distance Δx.

$$h_L = S_f \, \Delta x.$$

So, $\tau \, P \, \Delta x = \gamma \, S_f \, \Delta x A.$

The resultant force on the element of volume in the direction of motion is the resultant of the graistational, frictional, and pressure forces:

$$\rho g A S_0 \, \Delta x - \rho g A S_f \, \Delta x - \rho g A \frac{\partial y}{\partial x} \, \Delta x$$

The total rate of change of momentum is the sum of the local and convective momentum changes.

The acceleration of the fluid element is sum of local and convertive acceleration

$$\frac{dV}{dt} = \frac{\partial V}{\partial t} + \frac{V \partial V}{\partial x}$$

Therefore the product of mass $\rho A \, \Delta x$ and acceleration will give the rate of change of momentum i.e.

$$\rho A \, \Delta x \left(\frac{\partial V}{\partial t} + V \frac{\partial V}{\partial x} \right) = \rho g A S_0 \, \Delta x$$

$$- \rho g A S_f \, \Delta x - \rho g A \frac{\partial y}{\partial x} \, \Delta x$$

$$\frac{\partial V}{\partial t} + V \frac{\partial V}{\partial x} = g S_0 - g \frac{\partial y}{\partial x} - g S_f \qquad (2)$$

Equations (1) and (2) are the equations of unsteady flow. They serve as the basis of constructing the mathematical models for the investigation of numerous problems in unsteady flow.

2.3 Solution of Governing Equations:

2.3.1 Complete Solutions:

There are 3 approaches for solving the governing differential equations (1) analytical solution (2) approximate numerical solution (3) complete numerical solution.

It is only recently with the advent of high speed computers it became possible to get the complete numerical solution in a comparatively less time and with greater accuracy.

Numerical methods for the solution of differential equations can be established by replacing the derivatives by finite differences. The differential equations are then represented by corresponding algebraic equations. In spite of the fact that numerical methods donot require any drastic simplifications of the equations of unsteady flow, the procedure for representing the partial differential equations by algebraic

equations is not straight forward. Many factors involving convergence, stability, accuracy and efficiency come into picture. Although the procedure involved may be reduced to simple mathematical operations, the number of those operations may be extremely large, and this is true for application to most flood routing problems.

Methods for the numerical solution of the complete equations of unsteady flow based on finite difference schemes are broadly classified as direct methods and characteristic methods. Direct methods are those in which the finite difference representation is based directly on the primary equations. In the characteristic methods, the equations are first transformed in to the characteristic from and the latter form is used in finite difference representation. A fixed mesh of points on the time-distance plane is employed to identify the points at which solutions are obtained by the direct methods. In the characteristic methods, solutions may be obtained at the intersection of characteristic curves on the time-distance plane or at fixed points of rectangular mesh by interpolation between the intersection of characteristics.

The finite difference schemes used in the direct
and characteristic methods are further divided into
two - i.e. explicit and implicit methods.   In the
explicit methods, the finite difference equations from
which the unknowns can be evaluated explicitly a few
at a time.   The unknowns occur implicitly in the finite
difference equations of implicit methods, which are
usually non-linear algebraic equations.

Methods of Solution

Direct

Characteristic

Explicit   Implicit

Characteristic
nodes

Fixed mesh

Explicit   Implicit   Explicit   Implicit
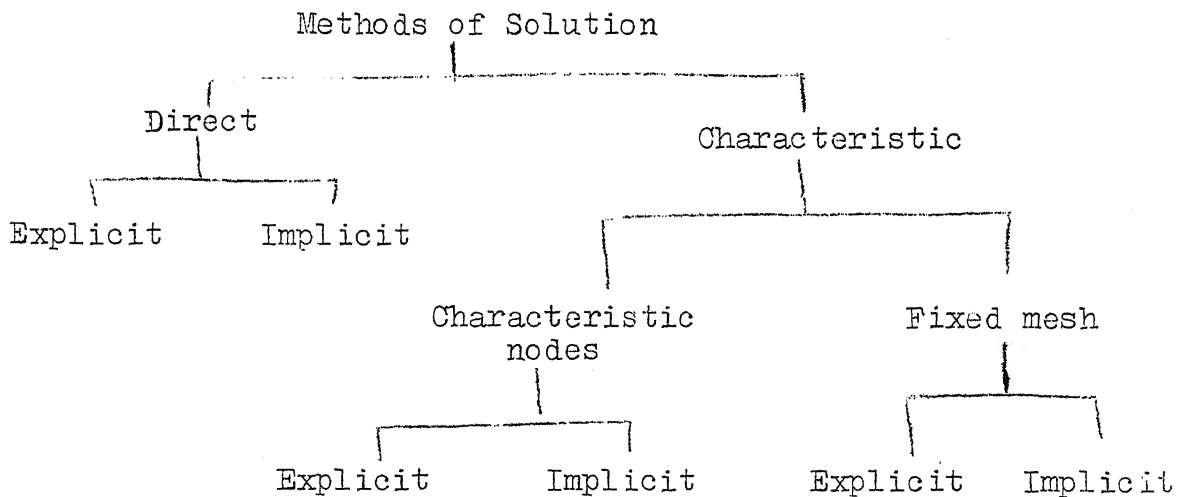
Out of all these methods, only three are more commonly
used.

1.   the implicit characteristic method using
        characteristic network.

2.   the explicit direct method.

3.   the implicit direct method.

The other methods have been found to be either unstable
for general flood routing problems or they were basically
similar to one of the three methods discussed above.

2.3.2 Implicit Method

In the implicit method, x derivatives are
replaced in terms of finite differences evaluated at
time to + Δt and thus the unknowns occur implicitly in
the resulting algebraic equations, solution of these
algebraic equation is more complex as compared to the
explicit method.

There are many schemes which have been
reported in the literature. Of these the following
have been used for studying the open channel transients:

Priessman's scheme [25], Amein's scheme [4],
Vasilev's scheme [26] etc.

While writing the expression for partial
derivative, a weighting factor α is introduced in the

Priessmann's and in Amein's schemes. The presence of
α introduces artificial damping in addition to the
damping due to friction and other losses. To make the
scheme stable, value of α must lie between 0.5 to 1.
Vasiliev's scheme has two steps and thus is more compli-
cated and requires more computer time. Keeping in
view the simplicity of Amein's scheme, it was preferred
to other ones.

Mozayaney and Song have used characteristic
method. But in this study implicit scheme was preferred.
The reasons are following:

(1) There is no restriction on Δt in this method.
     Since hydrographs with different rate of rise
     were attempted it was necessary to have some method
     which does not depend much on the nature of input
     data.

(2) Economy: Because the size of Δt is not
     stricted by any stability criterion, computer
     space requirement is less.

2.3.3 Details of Implicit Scheme

On the (x,t) plane, the net points are determined
by the intersection of straight lines parallel to the
x and t axes. The lines drawn parallel to the **t** - axis
represent locations along the channel while those
drawn parallel to the x-axis represent time. The
spacing of locations has been kept constant for the
present analysis. The t axis is the upstream channel
boundary. The downstream boundary condition is **steady**
flow.

The net work is drawn in Fig. 2.1. With reference
to the Fig. 2.1, assumed that all the variables are
known at all points of network on the row t^j i.e.
time step t^j and that it is desired to advance the
computation to time step

$$t^{j+1} = t^j + \triangle t$$

Here, the partial derivative at central point.
M of the network is defined as follows:

$$\alpha(M) = \frac{1}{4}(\alpha_i^j + \alpha_{i+1}^j + \alpha_i^{j+1} + \alpha_{i+1}^{j+1})$$

$$\frac{\partial \alpha}{\partial x}(M) = \frac{1}{2\,\triangle x}\left[(\alpha_{i+1}^j + \alpha_{i+1}^{j+1}) - (\alpha_i^j + \alpha_i^{j+1})\right],$$

$$\frac{\partial \alpha}{\partial t}(M) = \frac{1}{2\,\triangle t}\left[(\alpha_i^{j+1} + \alpha_{i+1}^{j+1}) - (\alpha_i^j + \alpha_{i+1}^j)\right]$$

where α may represent V, y, A, S_f or B.   In this conversion, the continuity equation now transforms to

$$\frac{1}{2\,\triangle t}\left[(y_{i+1}^{j+1} + y_i^{j+1}) - (y_{i+1}^j + y_i^j)\right] + \frac{1}{2\,\triangle x}V_{i+1/2}^{j+1/2}\left[(y_{i+1}^{j+1} + y_{i+1}^j)\right.$$

$$\left.-(y_i^{j+1} + y_i^j)\right] + \frac{1}{2\,\triangle x}(A/B)_{i+1/2}^{j+1/2}\left[(V_{i+1}^j + V_{i+1}^{j+1})\right.$$

$$\left.-(V_i^j + V_i^{j+1})\right] = 0$$

and momentum equation is,

$$\frac{g}{2\,\triangle x}\left[(y_{i+1}^j + y_{i+1}^{j+1}) - (y_i^j + y_i^{j+1})\right] + \frac{1}{2\,\triangle t}\left[(V_{i+1}^{j+1} + V_i^{j+1})\right.$$

$$\left.-(V_i^j + V_{i+1}^j)\right] + \frac{1}{2(\triangle x)}V_{i+1/2}^{j+1/2}\left[(V_{i+1}^{j+1} + V_{i+1}^j)\right.$$

$$\left.-(V_i^j + V_i^{j+1})\right] + \frac{g}{4}(S_{fi}^j + S_{fi+1}^j + S_{fi}^{j+1} + S_{fi+1}^{j+1})$$

$$-\frac{g}{\triangle x}(z_i^j - z_{i+1}^j) = 0$$

where

$$V_{i+1/2}^{j+1/2} = \frac{1}{4} (V_i^j + V_{i+1}^j + V_i^{j+1} + V_{i+1}^{j+1})$$

$$(V/A)_{i+1/2}^{j+1/2} = \frac{1}{4} \left[(V_i^j/A_i^j) + (V_{i+1}^j/A_{i+1}^j) + (V_i^{j+1}/A_i^{j+1}) \right.$$
$$\left. + (V_{i+1}^{j+1}/A_{i+1}^{j+1}) \right]$$

$$(q/B)_{i+1/2}^{j+1/2} = \frac{q}{4} \left[(\frac{1}{B_i})^j + \frac{1}{B_{i+1}}^j + \frac{1}{B_i}^{j+1} + \frac{1}{B_{i+1}}^{j+1} \right]$$

$$(A/B)_{i+1/2}^{j+1/2} = \frac{1}{4} \left[(A_i^j/B_i^j) + (A_{i+1}^j/B_{i+1}^j) \right.$$
$$\left. + (A_i^{i+1}/B_i^{j+1}) + (A_{i+1}^{j+1}/B_{i+1}^{j+1}) \right]$$

For friction slope at any point, Manning's formula is used in the above formulae all the variables with j superscript are unknown while those with $j+1$ are unknown.

These equations constitute a system of **two** nonlinear
algebraic equations in four unknowns. By themselves
they are not sufficient to evaluate the unknowns at
points i, j+1 and i+1, j+1.

Considering n points on any row, there will be
n-1 rectangular grids and n-1 interior points. The
combination of all the rectangular grids provides
2(n-1) equations for 2n unknowns. The two more equations
are provided by the u/s and d/s boundary.

Now, the channel reach is simulated by N-ordinate
lines on the x-t planes, a system of 2N nonlinear
algebraic equations for the solutions of 2N unknowns is
obtained. They are as follows:

$$F_0 \ (y_1, \ V_1) \ = 0$$

$$F_1 \ (y_1, V_1, \ y_2, V_2 \ ) \ = 0$$

$$G_1 \ (y_1, V_1, y_2 \ V_2) \ = 0$$

$$- \quad - \quad - \quad - \quad - \quad -$$

$$F_{n-1} \ (y_{n-1}, \ V_{n-1}, \ y_n, \ V_n) \ = \ 0$$

$$G_{n-1} \ (y_{n-1}, \ V_{n-1}, \ y_n \ V_n) \ = \ 0$$

$$F_N (y_N, \ V_n) \ = \ 0$$

General Equations

In the system of equations, the values of the variables at time step t^j are known and may be treated as constants. The unknowns are denoted by superscript $(j+1)$.

The upstream boundary condition is

$$y_1 = \lambda \qquad\qquad y_1 - \lambda = 0$$
$$d_{y1} = 0$$

The downstream boundary condition is

$$F_N(y_N, V_N) = Y_N - f_N(Q_N) = 0$$

For intermediate stations, equation of continuity takes the form,

$$F_i \left[\bar{y}_o, V_i, y_{i+1}, V_{i+1}\right] = (y_{i+1} + y_i) + a$$

$$+ \frac{1}{4} \frac{\Delta t}{\Delta x} \left[(y_{i+1} - y_i)(V_i + V_{i+1} + b) + C(V_i + V_{i+1})\right.$$

$$+ d\Big] + \frac{1}{4} \frac{\Delta t}{\Delta x} \left[(A_i/B_i) + (A_{i+1}/B_{i+1})\right]$$

$$\left[(V_i + V_i + e)\right] + \frac{1}{4} \frac{\Delta t}{\Delta x} \left[h\, V_{i+1} + m\, V_i + p\right] = 0$$

and the equation of motion is

$$G_i \left[y_i, \ V_i, \ y_{i+1}, \ V_{i+1} \right]$$

$$= (y_{i+1} - y_i + a') - \frac{\triangle x}{g \triangle T} \ (V_i + V_{i+1} + b')$$

$$+ \frac{1}{4g} \ (V_{i+1}^2 + c' \ V_{i+1} + d' \ V_i - V_i^2 + e' \ )$$

$$+ \frac{\triangle x}{2} \ (S_{fi} + S_{fi+1} + h') - 2. \triangle x \ (z_i - z_{i+1})$$

$$= 0$$

Here all non constant terms indicate the time step $j + 1$.

where a, b, c, d, e, h, p, w, a', b', c', d', e', h' are given interms of the variables at time step t^j.

$$a = -(y_{i+1}^j + y_i^j) \qquad a' = y_{i+1}^j - y_i^j$$

$$b = V_i^j + V_{i+1}^j \qquad b' = -(V_{i+1}^j + V_i^j)$$

$$c = y_{i+1}^j - y_i^j \qquad c' = 2V_{i+1}^j$$

$$d = (V_{i+1}^j (y_{i+1}^j - y_i^j) + V_i^j (y_{i+1}^j - y_i^j) \qquad d' = -2V_i^j$$

$$e = V_{i+1}^j - V_i^j \qquad\qquad e' = (V_{i+1}^j)^2 - (V_i^j)^2$$

$$h = A_i^j / B_i^j + A_{i+1}^j / B_{i+1}^j \qquad h' = S_{fi}^j + S_{f_{i+1}}^j + 2(z_i^j - z_{i+1}^j)$$

$$m = - \left(\frac{A_i^j}{B_i^j} + \frac{A_{i+1}^j}{B_{i+1}^j} \right)$$

Now the equation comprise of 2n nonlinear algebraic equation in 2n unknowns. They are

$$y_1 - \lambda = 0$$

$$F_1(y_1, V_1, y_2, V_2) = 0 \qquad\qquad G_1(y_1, V_1, y_2, V_2) = 0$$

$$F_2(y_2, V_2, Y_3, V_3) = 0 \qquad\qquad G_2(y_2, V_2, y_3, V_3) = 0$$

$$F_{N-1}(y_{N-1}, V_{N-1}, Y_N, V_N) = 0 \qquad G_{N-1}(y_{N-1}, V_{N-1}, Y_N, V_N)$$

$$F_N(y_N, V_N) = 0$$

In fact it is a very useful information that although the equations involve 2n unknowns, yet each equation contains a maximum of four unknowns.

Generalised Newton's Iteration Method

The application of generalised Newton's iteration method to the system of equations is made by assigning trial values to the unknowns.

$$
\begin{aligned}
&\phi_1 \left(\sigma_1, \sigma_2, \sigma_3, \ldots\ldots \sigma_{2N} \right) = 0 \\
&\phi_2 \left(\sigma_1, \sigma_2, \sigma_3, \ldots\ldots \sigma_{2N} \right) = 0 \\
&\quad - \quad - \quad - \quad - \quad - \quad - \quad - \quad - \\
&\quad - \quad - \quad - \quad - \quad - \quad - \quad - \quad - \\
&\phi_{2N} \left(\sigma_1, \sigma_2, \sigma_3, \ldots\ldots \sigma_{2N} \right) = 0
\end{aligned}
\right\} A
$$

Solutions are obtained by adjusting the trial values until residual vanishes or is reduced to a tolerable quantity. Let us indicate by suffix k the kth iterative value of σ_1, σ_2, σ_3 etc. It is desired to approximate the values of the variables through the (K+1)th cycle. When the values of the

variables are substituted into equation - - -**A**, the right side becomes the residuals. Let the residual be represented by R_i^k.

then

$$\phi_1 (\sigma_1^k, \sigma_2^k, \sigma_3^k, \ldots \ldots \ldots , \sigma_{2N}^k) = R_1^k$$

$$\phi_2 (\sigma_1^k, \sigma_2^k, \sigma_3^k, \ldots \ldots \ldots , \sigma_{2N}^k) = R_2^k$$

$$\phi_{2N} (\sigma_1^k, \sigma_2^k, \sigma_3^k, \ldots \ldots \ldots \sigma_{2N}^k) = R_{2N}^k$$

According to the generalised Newton's iteration method, the values of the variables are related by the following equations

$$\frac{\partial \phi_1}{\partial \sigma_1} d\sigma_1 + \frac{\partial \phi_1}{\partial \sigma_2} d\sigma_2 + \ldots \ldots + \frac{\partial \phi_1}{\partial \sigma_{2N}} d\sigma_{2N} = R_1^k$$

$$\frac{\partial \phi_2}{\partial \sigma_1} d\sigma_1 + \frac{\partial \phi_2}{\partial \sigma_2} d\sigma_2 + \ldots \ldots + \frac{\partial \phi_2}{\partial \sigma_{2N}} d\sigma_{2N} = R_2^k$$

$$\frac{\phi_{2n}}{\partial \sigma_1} d\sigma_1 + \frac{\partial \phi_{2N}}{\partial \sigma_2} d\sigma_2 + \ldots + \frac{\partial \phi_{2N}}{\partial \sigma_{2N}} d\sigma_{2N} = R_{2N}^k$$

where all the partial deviatives are evaluated at the
kth cycle,

$$d\sigma_1 = \sigma_1^{K+1} - \sigma_1^{k}$$

$$d\sigma_2 = \sigma_2^{k+1} - \sigma_2^{k}$$

— — — — — — — — — — —

— — — — — — — — — — —

$$d\sigma_{2N} = \sigma_{2N}^{k+1} - \sigma_{2N}^{k}$$

Now the above equation can be solved for $d\sigma_1$,
$d\sigma_2$, ... $d\sigma_{2N}$ and values of σ_1^{k+1},
σ_2^{k+1}, ... σ_{2N}^{k+1} can be easily found out.

This procedure is calculated till the residual is
negligible.

Solution of the finite difference Equations

The same procedure can now be illustrated with the
flood routing problem.

The equations are:

$$y_1 - \lambda = 0$$

$$F_1 \; (y_1, \; v_1^k, \; y_2^k, \; v_2^k) \; = \; R_{1,1}^k$$

$$G_1 \; (y_1 v_1^k, \; y_2^k, \; v_2^k) \qquad = \; R_{2,1}^k$$

$$F_i \; (y_i^k, \; v_i^k, \; y_i^k, \; v_i^k) = \; R_{1,i}^k$$

$$G_i \; (y_i^k, \; v_i^k, \; y_i^k, \; v_i^k) = \; R_{2,i}^k$$

$$F_{N-1} \; (y_{N-1}^k, \; v_{N-1}^k, \; y_N^k \; v_N^k) \; = \; R_{1,N-1}^k$$

$$G_{N-1} \; (y_{N-1}^k, \; v_{N-1}^k, \; y_N^k, \; v_N^k) = \; R_{2,\;N-1}^k$$

$$F_N \; (y_N^k, \; v_N^k) = R_{1,N}^k$$

The residuals and the partial derivatives
are related according to the generalised iteration
method by

$$dy_1 = 0$$

$$\frac{\partial F_1}{\partial y_1} = dy_1 + \frac{\partial F_1}{\partial V_1} \, dV_1 + \frac{\partial F_1}{\partial y_2} + \frac{\partial F_1}{\partial V_2} \, dV_2 = R_{1,1}^k$$

$$\frac{\partial G_1}{\partial y_1} \, dy_1 + \frac{\partial G_1}{\partial V_1} \, dV_1 + \frac{\partial G_1}{\partial y_2} \, dy_2 + \frac{\partial G_1}{\partial V_2} \, dV_2 = R_{2,1}^k$$

$$\frac{\partial F_{N-1}}{\partial y_{N-1}} \, dy_{N-1} + \frac{\partial F_{N-1}}{\partial V_{N-1}} \, dV_{N-1} + \frac{\partial F_{N-1}}{\partial y_N} \, dy_N' + \frac{\partial F_{N-1}}{\partial V_N} \, dV_n = R_{1,N-1}^k$$

$$\frac{\partial G_{N-1}}{\partial y_{N-1}} \, dy_{N-1} + \frac{\partial G_{N-1}}{\partial V_{N-1}} \, dV_{N-1} + \frac{\partial G_{N-1}}{\partial y_N} \, dy_N + \frac{\partial G_{N-1}}{\partial V_N} \, dV_N = R_{2,N-1}^k$$

$$\frac{\partial F_N}{\partial y_N} \, dy_N + \frac{\partial F_N}{\partial V_N} \, dV_N = R_{1,N}^k$$

where

$$dy_1 = 0, \quad dV_1 = V_1^{k+1} - V_1^k$$

$$dy_i = y_i^{k+1} - y_i^k, \quad dV_i = V_i^{k+1} - V_i^k$$

$$dy_N = y_N^{k+1} - y_N^k, \quad dV_N = V_N^{k+1} - V_N^k$$

All the partial derivatives are evaluated at the
kth iteration cycle. The solution of the system of
equation will provide values of y_i^{k+1}, V_i^{k+1}. The
procedure will be repeated many times until the desired
accuracy is achieved. The values of the variables found
in the terminal iteration cycle will be taken as the
values of the variables for the time step (j+1) and
the computations will be advanced to next time step (j+2).

The coefficients of the matrix are obtained by
diffentiating equations with respect to the
independent variables and are given below.

$$\frac{\partial F_i}{\partial y_i} = 1 - \frac{1}{4} \frac{\Delta t}{\Delta x} (V_i + V_{i+1} + b) + \frac{1}{4} \frac{\Delta t}{\Delta x} (V_{i+1} - V_i + e)$$

$$\left[1 - \left(\frac{A_i}{B_i^2} \right) \left(\frac{dB_i}{dy_i} \right) \right]$$

$$\frac{\partial F_i}{\partial y_{i+1}} = 1 + \frac{1}{4} \frac{\Delta t}{\Delta x} (V_i + V_{i+1} + b) + \frac{1}{4} \frac{\Delta t}{\Delta x} \left[1 - \left(\frac{A_{i+1}}{B_{i+1}^2} \right) \right.$$

$$\left. \left(\frac{dB_{i+1}}{dy_{i+1}} \right) \right] (V_{i+1} - V_i + e)$$

$$\frac{\partial F_i}{\partial V_i} = \frac{1}{4} \quad \frac{\Delta t}{\Delta x} \left[(y_{i+1} - y_i) + c \right] - \frac{1}{4} \quad \frac{\Delta t}{\Delta x} \left[(A_i/B_i) \right.$$

$$\left. + \left(\frac{A_{i+1}}{B_{i+1}} \right) \right] + \frac{m}{4} \frac{\Delta t}{\Delta x}$$

$$\frac{\partial F_i}{\partial V_{i+1}} = \frac{1}{4} \quad \frac{t}{x} \left[(y_{i+1} - y_i) + c \right] + \frac{1}{4} \quad \frac{\Delta t}{\Delta x} \left[(A_i/B_i) \right.$$

$$\left. + \left(\frac{A_{i+1}}{B_{i+1}} \right) \right] + \frac{h}{4} \quad \frac{\Delta t}{\Delta x}$$

$$\frac{\partial G_i}{\partial y_i} = -1 + \frac{2}{3} \ (\Delta x) \ Sf_i \left[\frac{1}{B_i} \left(\frac{dB}{dy} \right)_i - \frac{B_i}{A_i} \right]$$

$$\frac{\partial G_i}{\partial y_{i+1}} = 1 + \frac{2}{3} \ \Delta x \ S_{fi+1} \left[\frac{1}{B_{i+1}} \left(\frac{dB}{dy} \right)_{i+1} - \frac{B_{i+1}}{A_{i+1}} \right]$$

$$\frac{\partial G_i}{\partial V_i} = \frac{1}{g} \quad \frac{\Delta x}{\Delta t} - \frac{1}{2g} \quad V_i + \frac{d'}{4g} \quad \frac{\Delta x}{V_i} \quad S_{fi}$$

$$\frac{\partial G_i}{\partial V_{i+1}} = \frac{1}{g} \quad \frac{\Delta x}{\Delta t} + \frac{1}{2g} \left[V_{i+1} + \frac{c'}{2} \right] + \frac{\Delta x}{V_{i+1}} \ S_{f_{i+1}}$$

This numerical procedure was applied for routing the
flood through the channel.

2.3.4 Verification of the Programme

In the book Hydraulic Transients by Streeter and Wyle, in the Chapter open channel flow a problem of flood routing has been solved. The same problem was taken for checking the correctness of the program. The results obtained by the implicit method were compared with the solution obtained in the book. It was found that the depth compared very well in the two solutions. Velocity in the implicit scheme was higher than the characteristic method. But the difference was limited to the second decimal places. This validates the computer program.

CHAPTER III

LITERATURE REVIEW

The subsidence of wave in the channel with initial steady condition is the phenomenon of prime interest for any practicising engineer. The subsidence may be controlled by the resistance and acceleration terms in the dynamic equations of motion or by a much more simple mechanism of pondage in lakes through which the flood passes. But before going to the fundamentals and detailed analysis, it would be useful to have an idea of how other analysers have explained this phenomenon.

The simplest wave form as given by Seddon [21] or independently by Kleitz, is the monoclinal rising wave in a uniform channel. Scuh a wave consists of an initial steady flow, a period of uniformly increasing flow, and a continuing steady flow at the higher rate. Superimposing on this wave system a velocity v equal and opposite to the wave celerity,c causes the wave to become stationary and a steady flow known as overrun

is = $(c - v_1)A$ or $q - cA = $ constant

or $\dfrac{dq}{dA} = c = \dfrac{1}{B} \dfrac{dq}{dy}$

This is called Seddon law after the man who demonstrated its validity on the Mississippi River [21]. This Seddon's law is based on the assumption that q is a function of y alone. Secondly, it assumes that the wave form does not subside or diminish in shape which is contrary to the experience. To overcome these defects, concept of kinematic wave was introduced by Lighthill and Whitham [19]. These investigators defined a kinematic wave as one in which Q is a function of y alone; this imples $S_f = S_o$ and that the other slope terms are negligible. It can be easily shown that there can be a true wave motion when Q is a function of y alone, by considering the equation   continuity i.e.

$$\dfrac{\partial Q}{\partial x} + B \dfrac{\partial y}{\partial t} = 0$$

or $\dfrac{\partial Q}{\partial y} \dfrac{\partial y}{\partial x} + B \dfrac{\partial y}{\partial t} = 0$

or $\dfrac{dy}{dt} = \dfrac{dx}{dt} \cdot \dfrac{\partial y}{\partial x} + \dfrac{\partial y}{\partial t} = 0$

where $\dfrac{dx}{dt} = C = \dfrac{1}{B} \dfrac{dQ}{dy}$

Therefore, for an observer moving with a velocity c, y will appear to be constant and so Q will also appear to be constant. This leads to a very important conclusion that the Kinematic waves move with the same velocity as given by the monoclinal wave. At this stage dynamic wave can be introduced. This wave is obtained from the dynamic momentum equation and continuity equation. The kinematic waves lead to only one wave velocity while/the dynamic waves there are two possible wave speeds physically this means that a dynamic disturbance i.e. one in which all slope terms are important will propagate in both upstream and downstream directions. A kinematic disturbance will propagate in the downstream direction.

far

Actually there is possibility that both the kinds of wave motion are present in any natural flood wave. Since the bed slope term dominates the other slope terms, even if the latter ones are negligible, the main bulk of the flood moves substantially as a kinematic wave, although its character is modified by the other slope terms. Despite these arguments, the speed of the main flood wave may be expected to approximate

to that of the kinematic wave and the same has been
concluded by Lighthill and Whitham.

Henderson [14] in his papers white discussing the
flood wave characteristics has shown that the leading
dynamic wave acts as a fore runner of the main wave,
and if $F_O > 2$ this fore-runner will bring about appreciable
rise of the water level before the arrival of the main
wave. But in most of the natural flood wave problems,
F_O is seldom greater than 2 and so fore runner does not
play any singnificant role. In fact the discussion of
the fore-runner is of limited practical limited utility
while dealing with the natural flow problems. Henderson
has shown by qualitative analysis that there will be
appreciable subsidence of the flood wave. The space
rate of subsidence is itself a small fraction of the
bed slope. In the most of the flood routing problems,
to avoid time consuming calculations, a much simplified
approach was adopted by the practicising engineers. The
flood wave movement can be simulated by an electric
analogy in which a pulse is fed into the system. This
pulse can be attenuated either by a capacitance or by a

resistance. When effect of capacitance is dominant or hydraulically, when effect of storage is important it is called storage routing. Thomas [28] used graphical method of integration of the governing equations namely continuity and momentum equation in his analysis. He used the simplified form of equation of motion by neglecting second order terms. This method requires the contour map of the area and is also crippled with tedious time consuming graphical approach.

The best known approximate methods for the integration of the equations of unsteady flow are the so called storage routing [20] methods. In a typical method the equation of continuity without lateral flow is represented in finite difference form as

$$\frac{\Delta Q}{\Delta x} = \frac{\Delta A}{\Delta t} \quad \text{or} \quad \Delta Q = \frac{\Delta A}{\Delta t} \cdot \Delta x$$

$\Delta A \cdot \Delta x$ is nothing but the change in the volume or the change in storage i.e.

$$\Delta S = \Delta A \cdot \Delta x \quad \text{where } S = \text{storage}$$

$$\Delta Q = \frac{\Delta S}{\Delta t}$$

$$O - I = \frac{\Delta S}{\Delta t}$$

This equation is the equation of continuity. Another widely used storage routing method is the Muskingum method [20]. This is called Muskingum method because it was applied in the river Muskingum at Ohio. In this method the storage-discharge relationship is given by an empirical equation the coefficients of which are obtained from historical records. This method is described in any of the text books [20, 21]. Brakensiek and Comer (1966) gave an approximate approach in which the equation of continuity is retained and the momentum equation is simplified to $(\partial y/\partial x) = S_o - S_f$ by neglecting the accelerating terms.

Approximate methods whether numerical or analytical provide solutions which are useful and accurate but the serious disadvantage is as regards the uncertainty in accuracy of solution. With the use of high speed computers, attempts were made to solve the complete equations numerically. The one such attempt was made by M. Amein in 1966 [3], Freed (1973), Baltzer etc. These methods were computer based and so the degree of accuracy can be taken to any desired degree of accuracy. Amein [4] in report has shown how successfully

the implicit scheme can be used for an irregular channel.
Out of all the methods namely explicit, characteristics
and implicit, the last one has been found to be most
stable.

The parametric study of flood wave propagation in
a part full pipe was done by Peter Ackers and A.J.M.
Harrison [1] in 1964. The work was published in the
Proceedings of the Institution of Civil Engineers 1964,
Vol. 28. Their study was for a pipe flow. They studied
only the subsidence of peak depth. In 1969, Mozayaney
and Song also presented a parametric study on the flood
propagation. They used a sinusoidal hydrograph. The
wave amplitude and duration etc. were very small so that
they are most suited for a small flume.

In a very recent paper, Sridharan and Mohan Kumar [26]
studied the effect of various parameters in the case of
open channels. They have nondimensionalised the equations of
continuity and equation of momentum. This study is a
good approach towards the parameteric studies. But
they covered a lot of independent variables and thus
complicating the study.

CHAPTER IV

FORMULATION OF THE PROBLEM

4.1 General

It is obvious from the theory that it is very
difficult to solve the governing equations analytically
for various practical problems. The numerical techniques
are very complicated and for accuracy high speed computer
is required. Keeping in view all these things it was
considered desirable to carry out a systematic dimensional
analysis and determine the variation of the important
dimensionless parameters relating to flood propagation as
the pertinent independent parameters are varied systematically.

4.2 Dimensional Analysis

4.2.1 General

One of the important dependent variables of
interest in flood routing through a river is the subsidence
or decay of the wave amplitude with distance. This subsidence
is defined as the depth at any section minus initial steady
depth, non-dimensionalised by the net increase in
stage at the initial station. In other words this term
gives the wave amplitude at any section normalised by the

initial wave amplitude at x = 0.   Mathematically,

$$Y_* = \text{Relative wave amplitude}$$

$$= \frac{(Y_p)_{x=i} - Y_o}{(Y_p)_o - Y_o}$$

The other important variable is the time of travel of the peak. The time lapse between the occurrence of peak stage at the initial station and at any stations (downstream) is equal to the time of travel of the peak. The time of peak depth, expressed as T_p is non-dimensionalised by $x/(V_o + C_o)$ which is the theoretical time taken by the wave to reach at particular location. This non-dimensionalised time presents an idea of how the wave is moving in time space plane. Too large value of it means that small amplitude waves are coming first and peak of the hydrograph has not been reached. Similarly if it becomes small, it means the wave is moving with the peak depth.

4.2.2 Dimensional Analysis

The independent variables are the initial uniform flow depth Y_o, distance of the section under consideration x, Manning's n, initial Froude No F_o, time of peak of the hydrograph t_p, time to centre of gravity of the hydrograph t_g, peak depth of the hydrograph y_w, rate of rise of

the rising limb described as y_w/t_p, nature of the hydrograph.

Mathematically,

$$Y_* = f_1(x, y_0, n, y_p, F_0, t_p, t_g, \frac{y_w}{t_p}, \text{shape of the hydrograph})$$

$$\frac{T_p}{x/(V_0 + C_0)} = f_2(x, y_0, n, y_p, F_0, t_p, t_g, \frac{y_w}{t_p}, \text{shape of the hydrograph})$$

Dimensionless grouping of the above variables leads to the following two equations

$$Y_* = f_1(\frac{x}{y_0}, n, F_0, \frac{t_p}{t_g}, \frac{y_p}{y_0}, \frac{y_p - y_0}{t_p(V_0 + C_0)}, \text{shape of the hydrograph})$$

$$\frac{\frac{T_p}{x}}{(V_0 + C_0)} = f_2(\frac{x}{y_0}, n, F_0, \frac{t_p}{t_g}, \frac{y_p}{y_0}, \frac{y_p - y_0}{t_p(V_0 + C_0)}, \text{shape of the hydrograph})$$

where F_0 = Froude no. at initial steady flow

$$= \frac{q_0}{y_0\sqrt{g\, y_0}} \; ; \; g \text{ is the acceleration due to gravity}$$
$$= 9.81 \text{ m/sec.}^2$$

$$V_0 = \frac{q_0}{y_0} \; ; \; q_0 \text{ is initial steady discharge}$$

$$C_0 = \sqrt{g\, y_0}$$

$$\frac{y_p - y_0}{t_p(V_0 + C_0)} = \text{dimensionless rate of rise of the hydrograph.}$$

4.3 Parametric Study

The important factors which control the movement of flood waves in the regular channel can be classified into 3 groups.

(i) Channel Geometry

(ii) Flow Condition

(iii) Initial Conditions

The variables in each are as follows:-

1. Channel Geometry

   (a) Cross-sectional shape

   (b) Channel bed slope

   (c) Roughness of the channel expressed as Manning's coefficient n

2. Flow Condition

   (a) Upstream boundary condition- given by the inflow hydrograph

   (b) Base flow

   (c) Peak depth of flow

   (d) Time to reach peak of the hydrograph

   (e) Time to the centre of gravity of the hydrograph.

3. Initial Condition

   (a) Steady uniform flow

   (b) Steady nonuniform flow.

4.4 Range of Variables

4.4.1 Froude Number F_O

In most of the natural rivers the flow is in subcritical state and leaving the initial reach at its mouth , the river flows in tranquil state.

In their recent paper of ASCE [26] , the authors have concluded that the Froude number does not have significant effect on the subsidence in the case of wide channels. Keeping in view the large number of computer experiments it was decided to use the most suitable single value for Froude Number. This value has been taken as equal to 0.3.

4.4.2 Cross-section area

The simplest one is rectangular shape. So rectangular section was adopted.

4.4.3 Manning's n

Manning's n was varied from 0.02 to 0.03. It was not possible to go beyond n =0.03 for $y_w/y_o > 3$ as there was local supercritical flow.

4.4.4 Wave amplitudes

y_p/y_o: In most of the flood problems the maximum depth of flow comes out to be nearly 3 times the steady

depth. So y_p/y_o was varied from 1.5 to 3.

4.4.5 $\dfrac{t_p}{t_g}$

The worst flood has a value of 1/3 and the other one was 2/3.

4.4.6 Inflow hydrograph

Inflow hydrograph used are of three types:

(1) Sine curve

(2) +vely skew hydrograph of type III

(3) Triangular hydrograph adjusted in (2) above.

Sine curve was not used in the further analysis as it does not resemble the real flood problem. The suitability of +vely skew hydrograph bound in the direction of zero has been discussed with details in Chapter V.

The equation of the hydrograph used was

$$\frac{y}{y_o} = 1 + \frac{y_w}{y_o} \left[e^{-\frac{(t-t_p)}{(t_g-t_p)}} \right] \left[\frac{t}{t_p}\right]^{(t_p/(t_g-t_p))}$$

where all terms have been defined earlier.

CHAPTER V

ANALYSIS OF RESULTS

5.1 General

Based upon the dimensional analysis all the
variables were non-dimensionalised. Various graphs were
plotted between relative wave amplitude and distance with
one more variable keeping all others constant. This
sort of analysis will give an insight into the compli-
cated phenomenon of wave propagation.

But the first question arises as to what the
shape of the inflow hydrograph should be. Mozayaney
and Song in their paper [26] have used sinusoidal
hydrograph.   But in actual field observations no
hydrograph is strictly sine curve, rather they have
steeply rising limb and comparatively flatly falling
limb. So it was considered more justified to use
skewed (to the left) hydrograph in place of symmetrical
ones. That the hydrograph should be +vely skewed
one can be shown from the argument which follows here.
Refer to Fig. 5.1. The hydrograph at the origin of the
river is nearly symmetrical. But the falling limb

has a velocity $= V + C$ while the rising limb has $V-C$ where C is 'celerity $= \sqrt{gyo}$ which of-course will die out as it travels upstream. But if temporal distribution of flood wave is considered, it can be concluded that the rising limb will remain steep but falling limb will loose its steepness very quickly. Modification of wave with distance and time is shown in figure 5.2 which also supports the statements made here.

Before proceeding to further analysis some terms are defined here.

(a) Rate of subsidence is described as Relative wave amplitude $Y_* = \dfrac{(y_{peak})_{x=i} - y_0}{(y_{peak})_{x=0} - y_0}$.

The relative wave amplitude gives the maximum wave amplitude at any section normalised by the same at $x = 0$.

(b) Relative discharge rise

$$Q_* = \frac{Q(q_{max})_{x=i} - q_0}{(q_{max})_{x=0} - q_0}$$

(c) $\quad T_* = \dfrac{T_P}{x/(V_o + C_o)}$

i.e. time taken by wave peak to reach any station since the starting of the hydrograph non-dimensionalised by the theoretical time taken to reach that section.

5.2 Analysis of rate of subsidence:

To analyse this following graphs were plotted

(1) Y_* VS X with different rate of rise of the hydrograph.

(2) Y_* vs X with different Y_W keeping tp/tg = constant.

(3) Y_* vs X with different tp/tg values keeping Y_W = constant

(4) Y_* VS X with n.

5.2.1 Effect of n:

Plots of relative wave amplitude Y_* and X with Manning's n as the third parameter indicate that Mannings n has very significant effect on the subsidence.

From the graphs, it can be seen that an increase in
mannings roughness coefficient result in the increase
of relative wave amplitude.

For n = 0.02, Y_* = 0.550 for tp/tg = 2/3 at x = 16

for n = 0.03, Y_* = 0.685 for tp/tg = 2/3 at x = 16.

Therefore, the effect of Mannings n is to decrease the
subsidence. When Mannings n increases the wave pass
es   without getting subsided. This may be
explained from the momentum equation.   Energy slope
is directly dependent upon mannings n and so with the
increase in manning's n, energy slope S_f also increases.

$$\frac{\partial V}{\partial t} + V \frac{\partial V}{\partial x} + g \frac{dy}{dx} = g\,S_0 - g\,S_f$$

Now, the right hand term diminish and so do the left
hand terms, i.e., the acceleration term decreases. This
appears to be the possible explanation of this effect
of mannings n.

5.2.2 Effect of Wave Amplitude Y_w

The variation of wave amplitude Y_* with X
keeping tp/tg constant is plotted in the figure 5.3 and 5.5.

From these curves it is clear that relative wave
amplitude increases with increase in Y_W. This
increase is small as compared to the effect of
Manning's n.

Secondly, it can be seen that the steepness of
the plotted curve decreases with the increase in distance
X. The wave in later reaches tend to become flatter,
and the subsidence in the later reaches has been found
to be more. In the initial reaches Y_* and X vary in a
straight line pattern. The same conclusion has been
confirmed by Sridharan [26] in his paper. In fact this
straight liness is true for small length of the river.
Lyer used 30 km of channel length and his conclusions
also support the straight line nature.

5.2.3 Effect of tp/tg:

The plots of Y_* with X for different tp/tg
values are presented Fig. 5.6 and 5.7. Y_* decreases
linearly with X in the initial reaches. The line tends
to become flatter with increase in distance. The rate

of change in slope decreases with distance. The
effect of tp/tg is to increase the relative wave
amplitude Y_*. This effect is more pronounced than the
effect of wave amplitude Y_w.

Subsidence is more in the later reaches. This
can be explained as follows. When the wave has
flattened sufficiently in the lower reaches, the waves
become short duration ones and rate of subsidence
increases significantly.

5.2.4 Effect of Rate of Rise of the Hydrograph:

Rate of rise of the hydrograph is defined as yw/tp.
From the computed results of rate of rise of hydrograph
it was found that this term practically has no effect
on the relative wave amplitude. Fig. 5.2 clearly shows
this. In fact this rate of rise is taken into account
jointly by yw/yo and tp/tg and so this term can be
ignored.

5.2.5 Effect of shape of the Hydrograph:

Keeping tp/tg, yw/yo, n same various runs of
the computer experiment were made by using triangular

hydrographs. From the computed results it was found
that the shape does not play much role in subsidence
phenomena. Although in case of tp/tg = 1/3, the
triangular shape showed a little more subsidence than
the +vely skewed hydrograph. This can be explained as
follows In the case of triangular hydrographs of very
steep rate of rise, the falling part gives more depth
than the +ve skewed hydrographs and so the cumulative
effect of the triangular hydrograph is slightly larger
subsidence. This/shown in figure 5. 9. The above
mentioned two conclusions are very significant. Now
only n, yw/yo, tp/tg remain to be studied.

5.3 Rating Curves:

A graphical representation of stage vs discharge
is called a rating curve. Such a rating curve for a
typical case is plotted in Fig. 5.3(c) The rating
curve clearly indicate that there are two values of
stage for one discharge. On the rising side the
discharge is more for the same stage as compared to
the falling side. Secondly with increase in distance

looping curve tends to become thinner meaning thereby
unique value of the discharge for one value of the
stage. The first observation leads to the belief that
the discharge is not a single valued function of stage
or discharge is a function of some thing else other
than the stage. In fact during the period of rise of
the hydrograph discharge is more but after the peak
of the hydrograph, discharge falls down owing to the
reverse slope of water surface.

5.4 Analysis of Time of Occurrence of Peak Depth:

Time of occurrence of peak is defined as the time
of occurrence of flood peak at a particular section in
the reach minus the time of occurrence of flood peak at the
initial station. This is the actual time of travel of the
peak.

5.4.1 Effect of n:

From the computation of results it became clear
that Manning's n plays practically no part in the time
of occurrence of peak. Previously in the analysis of
relative wave magnitude this very term was found to be

a dominating factor. It confirms that in the left

hand terms the effect of temporal

acceleration is little as compared to the spatial

acceleration.

Time to peak is non dimensionalised by the

theoretical time taken by the kinematic wave to reach the

section and the plot indicates that $\dfrac{T_p}{x/(Vo+Co)}$ is

independent of mannings n. Therefore it can be

concluded that time to peak bears a constant ratio with

the theoretical time taken by the wave to reach at the

same section.

5.4.2 Effect of Y_w

Graphical representation of $\dfrac{T_p}{x/(Vo + Co)}$ vs X

with Y_w as third variable indicates the following

points. One is that in the initial reaches there is very

steep fall in time to peak. This is probably due

to the discontinuity of the term $T_p/(x(Vo+Co))$ at x = 0.

Secondly, in the later reaches the ratio begin to

decrease with distance or time to peak is quickly

reached at the section under consideration. Thirdly,

the $T_p/(x(Vo + Co))$ value tend to become constant in the

further reaches. Fourthly, the effect of initial wave ratio Y_W is that with the increase in Y_W, $\frac{T_p}{x/(V_o+Co)}$ increases or lag of time to peak with theoretical time increases. So it can be concluded at this stage that the effect of initial wave ratio is very significant in the analysis of time to peak. This property can be of great use in the prediction of time to peak as will be shown in the next article.

5.4.3 Effect of tp/tg:

If time to peak T_p is nondimensionalised by theoretical time required to travel a distance is plotted with distance x, it is found that tp/tg of the hydrograph is not very important variable.

Therefore it appears that the wave travels with a velocity which is independent of the tp/tg ratio of the hydrograph. This conclusion has been confirmed by Sridharan [20] also.

5.5 Prediction of Y_p and T_p

5.5.1 General

In any flood routing problem, the engineer is interested in finding the magnitude of the maximum stage, maximum flood and time of their occurrence. By the computer solution based on numerical methods, one gets detailed picture of the surface profile, stage at any time at any section etc. which are not of much use to a practising engineer. Further the computer programmes are very complicated and require a lot input data in an specified form. All these factors call for a direct short-cut method for the prediction of peak stage and time of its occurrence.

After the detailed study of wave propagation based on dimensional analysis it is now possible to drop one or even more of the variables as their relative effect on the dependent variables is less.

5.5.2 Principle

From the previous study in this chapter, it can be concluded that for the rate of subsidence of relative wave amplitude is not dependent upon shape of the hydrograph,

rate of rise of the hydrograph, wave amplitude Y_W. The most important variables affecting Y_* are Manning's n and t_p/t_g. A plot of $1-Y_*$ on natural scale and X on logarithmic scale indicates that after some initial points, the points lie approximately on a straight line. This plot indicates that

$$1-Y_* = Y^+ = c + m \log_{10}(X)$$

where c and m are functions of n and t_p/t_g.

i.e. $c, m = f_{1,2} (n, \dfrac{t_p}{t_g})$

This is a very important conclusion and forms the basis of prediction of Y_* . Similarly from the analysis of time to peak stage, it is clear that it depends only upon Y_W and X. This forms the basis of prediction of time of peak stage.

5.5.3 Procedure for graphical prediction

(a) Relative wave amplitude

On a semilog paper, X is plotted on logarithmic scale as abscissae and $1-Y_* = Y+$ as ordinate on arithmatic scale.

After some of the initial points, which correspond to the straight lime portion of the Y_* vs n plot, a straight line is approximately fitted through them. The slope and intercept of the lines can be calculated by taking any two points on the straight line and solving them for m and c, where m = slope of the line, c = intercept on Y_+ axis.

$$now, \quad m, \ c \ = f_{1,2} \left(n, \ \frac{t_p}{t_g} \right)$$

So, m and c are plotted on a simple graph paper with n on abscissae and t_p/t_g as the third variable.

Since some error is caused due to neglecting of effect of t_p/t_g a suitable additive constant should be used for each y_w value.

(b)   Time of peak $T_* = \dfrac{T_p}{x/(V_o+C_o)}$

A plot of T_p/t_g on ordinate and X on abscissae with y_w as the third parameter is prepared. The dotted lines on the plot indicate the interpolated variation T_p/t_g and X with other y_w values.

	Additive Constant for Y_*		
Y_w =	0.5	1	1.5
Constant to be added to = Y_*	0.015	0.02	0.035

5.5.4 Steps

Data required:

Initial steady discharge q_o, Manning's n, t_p/t_g of the inflow hydrograph. Slope of the channel s distance of the section under consideration x time to centre of gravity of the hydrograph.

(1) From Manning's equation initial steady depth should be computed:

$$\text{i.e.} \quad y_o = \left| \frac{q_o \, n}{s} \right|^{3/5}$$

(2) For the given x, $X = \dfrac{x}{y_o}$ is calculated.

(3) Using the plot of Fig. _6-2_ , against t_p/t_g and n value m and c are calculated.

(4) Now,

$$Y^+ = m \log_{10} X - C$$

$Y+$ can be calculated.

(5) $Y_*' = 1 - Y^+$

(6) $Y_* = Y_*' + \text{additive constant}$.

This additive constant has to be interpolated from the table given above.

(7) $\qquad Y_* = \dfrac{(y_{peak})_{x=i} - y_o}{(y_{peak})_{x=0} - y_o}$

from this $(y_{peak})_{x=i}$ can be calculated.

(8) $\qquad$ Now coming to the Fig. $\qquad$ 6.3.

$\qquad$ From this plot for the given X and Y_W of the hydrograph, T_p/t_g can be noted down and t_g being known T_p can be calculated.

Illustration

$\qquad$ For x $= 500$ Km, $n = 0.02$, $Y_W = 1.0$

$\qquad\qquad$ x $= \dfrac{500 \times 10^3}{5} = 10^5 \qquad t_g = 12$ hrs.

$\qquad$ for n $= 0.02$ and $\dfrac{t_p}{t_g} = \dfrac{2}{3}$

$\qquad\qquad$ m $= 0.044$

$\qquad\qquad$ c $= 1.845$

$\qquad$ Y+ $= -1.845 + 0.44 \log_{10} 10^5 = 0.355$

$\qquad$ Y'_* $= 1 - 0.355 = 0.645$

$\qquad$ Y_* $= 0.44 + 0.02 = 0.665$

$\qquad$ y $= 0.665 \times 5 + 5 = 8.325$

which resembles very closely with the value of 8.26 m.

For time to peak, $T_p = 12 \times 3.30 = 39.6$ hrs. $\quad$ 40 hrs.

From the computed results also, we get $T_p = 40$ hrs.

Limitation

(1)   The magnitude of numerical damping is not known.

(2)   This is strictly for skewed hydrographs but can be used safely with triangular hydrographs for t_p/t_g upto 1/3.

(3)   There should not be local supercritical flow.

CHAPTER VI

6.1 Conclusions

The parametric study on the propagation of a flood wave in open channel leads to the following conclusions:-

1. There is significant subsidence in open channels.

2. Manning's roughness coefficient has significant effect on the subsidence expressed as relative wave amplitude.

3. The non-dimensional time to peak is found to be unaffected by the manning's n.

4. Shape of the hydrograph does not matter much in wave subsidence.

5. Rate of rise of the hydrograph does not affect the rate of subsidence.

6. Inflow wave amplitude Y_w has some influence on subsidence.

7. Wave peak duration t_p/t_g has pronounced effect on subsidence.

8. Non-dimensional travel time is very much affected by the wave amplitude and is not affected by t_p/t_g.

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TABLE

RANGE OF VARIABLES

$y_o = 5m, \quad t_g = 12\,hrs$

Set No.	Froude No. F_o	Wave amplitude Y_w	$\dfrac{t_p}{t_g}$	Manning's Roughness n	Slope S_o
1	0.3	0.5	2/3	0.02 0.025 0.03	0.21×10^{-3} 0.32×10^{-3} 0.47×10^{-3}
2	0.3	0.5	1/3	0.02 0.025 0.03	0.21×10^{-3} 0.32×10^{-3} 0.47×10^{-3}
3	0.3	1.0	2/3	0.02 0.025 0.03	0.21×10^{-3} 0.32×10^{-3} 0.47×10^{-3}
4	0.3	1.0	1/3	0.02 0.025 0.03	0.21×10^{-3} 0.32×10^{-3} 0.47×10^{-3}
5	0.3	2.0	2/3	0.02 0.025 0.03	0.21×10^{-3} 0.32×10^{-3} 0.47×10^{-3}
6	0.3	2.0	1/3	0.02 0.025 0.03	0.21×10^{-3} 0.32×10^{-3} 0.47×10^{-3}

Effect of Rate of Rise of Hydrograph

Set No.	F_o	Y_w	t_p/t_g	Rage of Rise	Manning's n
1	0.3	1	2/3	9.7×10^{-5}	0.02
2	0.3	1	2/3	7.5×10^{-5}	0.02
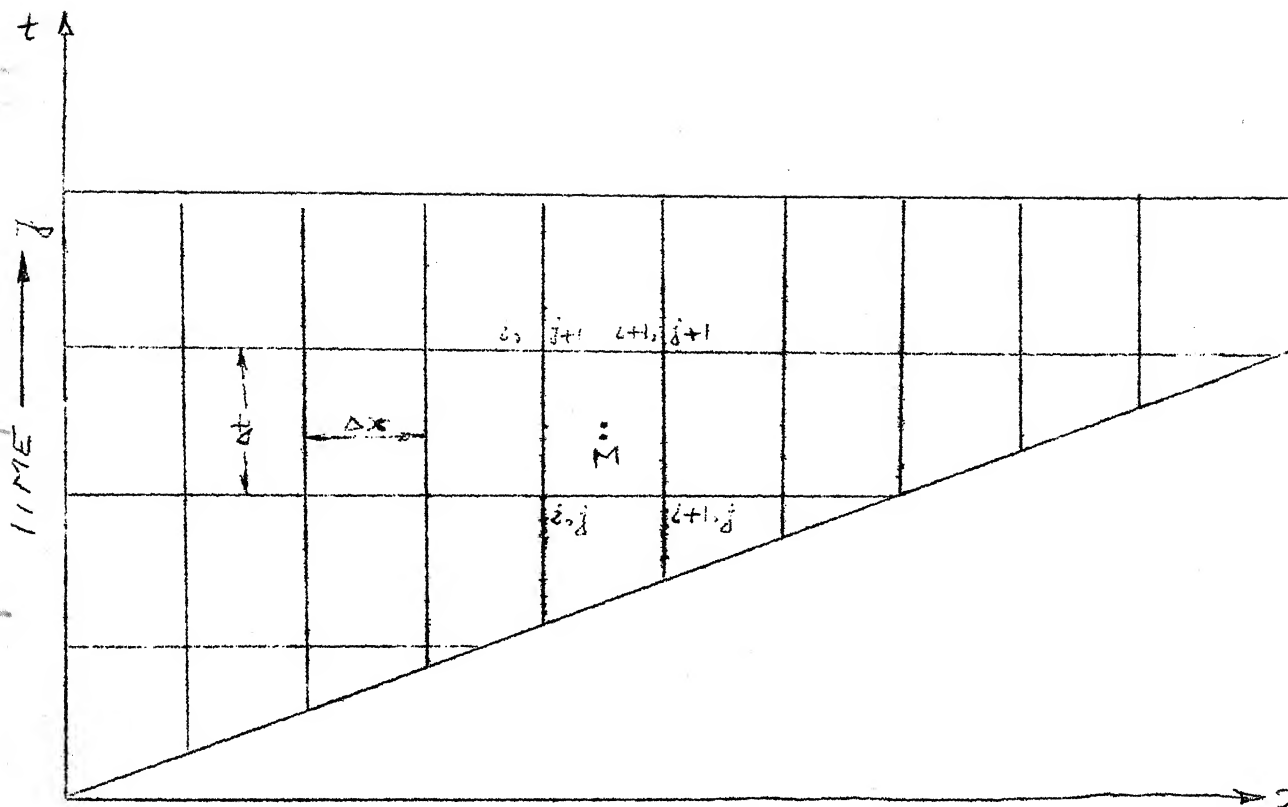
DISTANCE i ⟶

REPRESENTATION OF NETWORK

FIG. 2.1

Legend

$$Y = \frac{y}{y_0}$$

$$Y = 1 + \frac{y_P}{y_0} \; e^{-\frac{(t - t_P)}{(t_g - t_P)}} \left(\frac{t}{t_P}\right)^{t_P/(t_g - t_P)}$$

y_P = Peak increase above steady water level at $x = 0$

Wave height (Y)

T (hrs)

t_P

Wave height (Y)

T (hrs)

SYMMETRICAL WAVE

t = t₀

Fig 5.1

FIG.5·2 SPATIAL PICTURE OF SUBSIDENCE WITH TIME
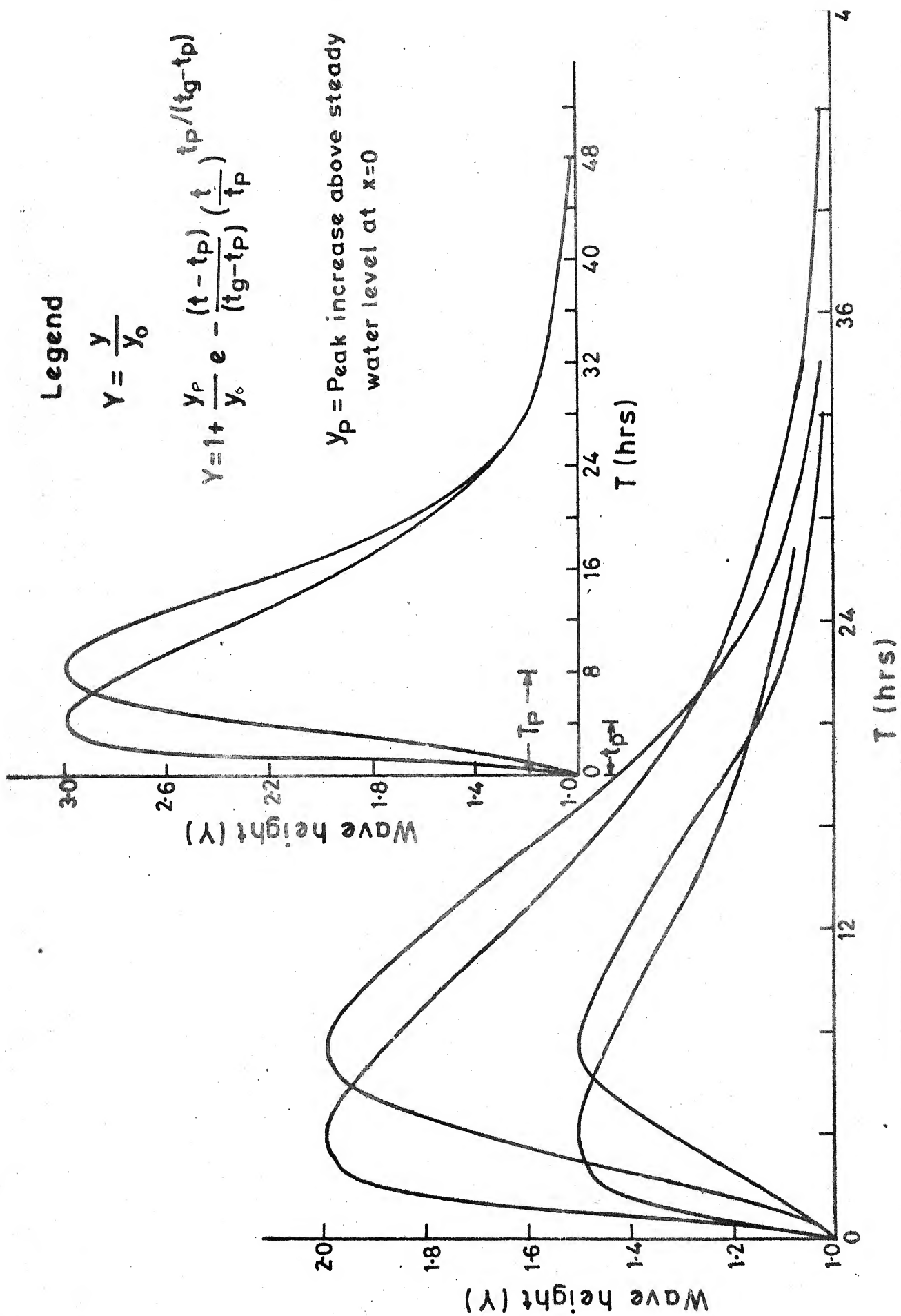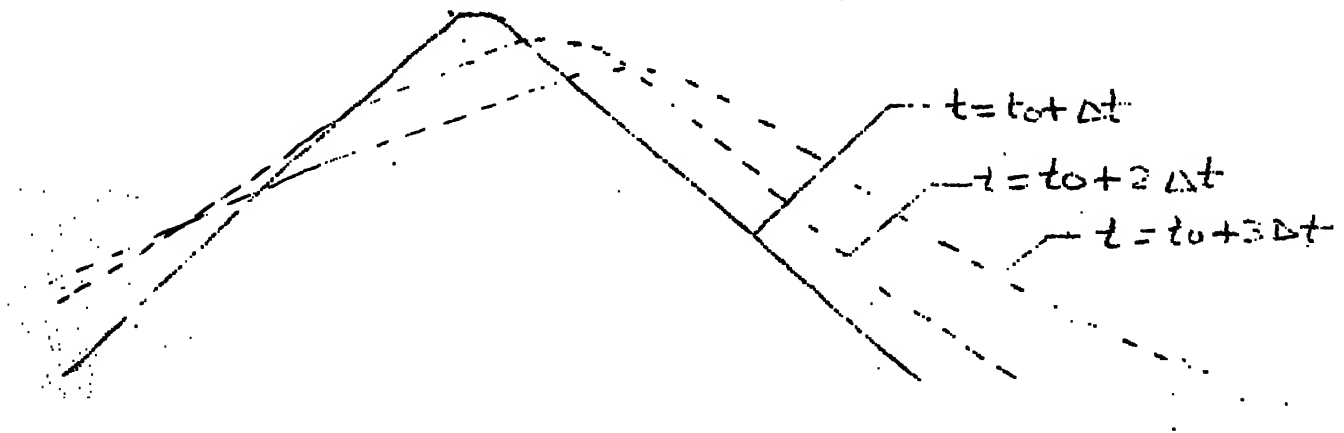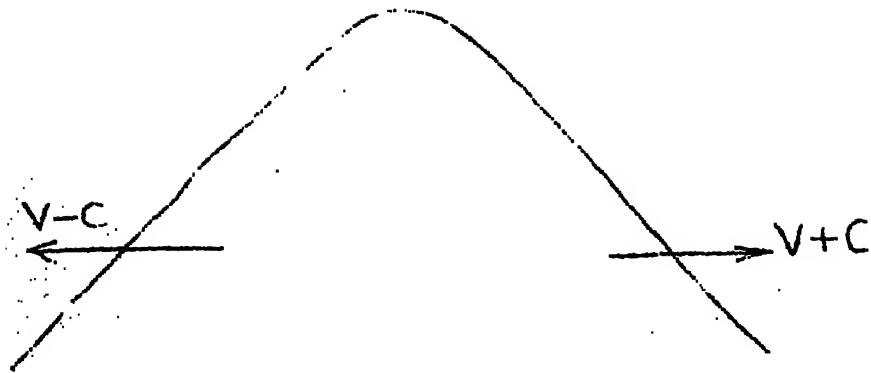
$n = 0.025$

$\dfrac{t_p}{t_g} = \dfrac{2}{3}$

$Y_w = 0.5$

Numbers in the curve indicates time in hrs

$X = \dfrac{x}{y_0} \times 10$

$Y = \dfrac{y}{y_0}$

FIG. 53 EFFECT OF n AND Y_w ON SUBSIDENCE OF FLOOD WAVE

Legend:
1. $n=0.02$, $Y_w=0.5$
2. $n=0.025$, $Y_w=0.5$
3. $n=0.03$, $Y_w=0.5$
4. $n=0.02$, $Y_w=1.0$
5. $n=0.025$, $Y_w=1.0$
6. $n=0.03$, $Y_w=1.0$
7. $n=0.02$, $Y_w=2.0$
8. $n=0.025$, $Y_w=2.0$
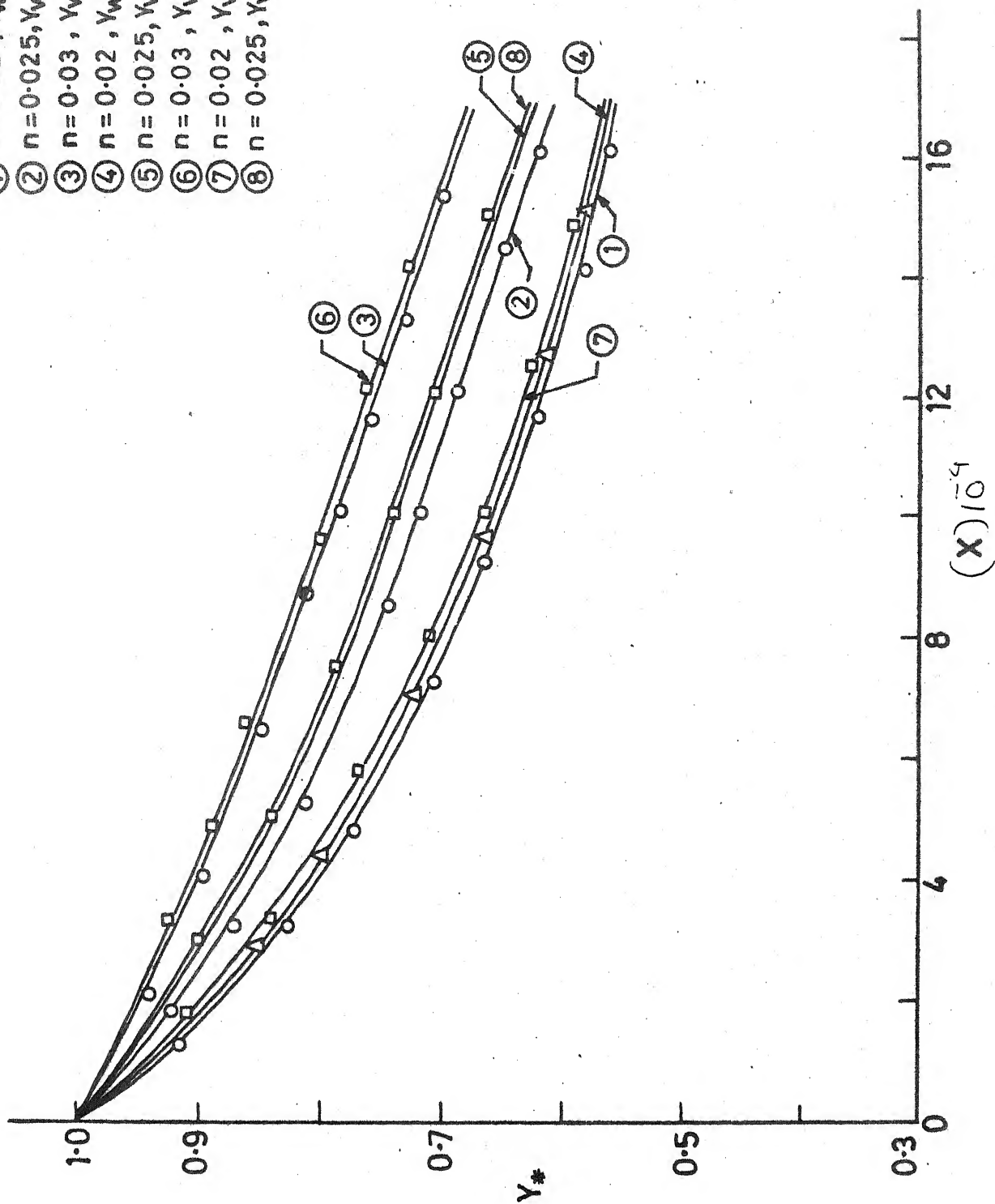
Y-axis: Y_*

X-axis: $(X) 10^{-4}$

$$Y_* = (y_P - y_o) / ((y_P)_{x=0} - y_o)$$

$$Q_* = \frac{q_{max} - q_o}{(q_o)_{max} - q_o}$$

RATING CURVE $n = 0.02$, $Y_w = 1$, $\frac{t_P}{t_g} = \frac{2}{3}$

LOGPEARSON TYPE III HYDROGRAPH

FIG. 5·3 &LOOP RATING CURVES

Legend:
① $n = 0.02$, $t_P/t_g = 2/3$
② $n = 0.025$, $t_P/t_g = 2/3$
③ $n = 0.03$, $t_P/t_g = 2/3$

Y-axis: Q_*

X-axis: $(X)/\bar{0}^{-4}$
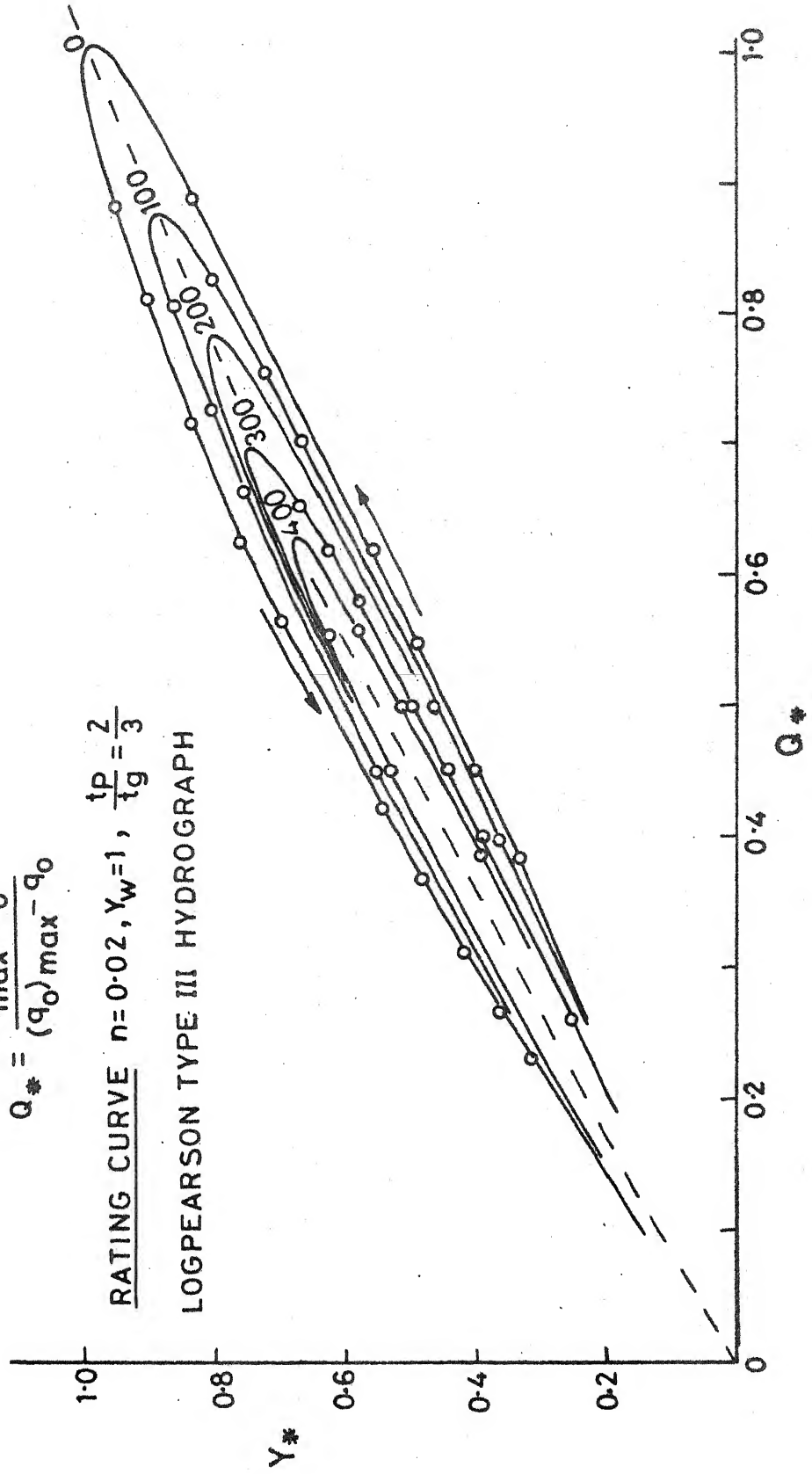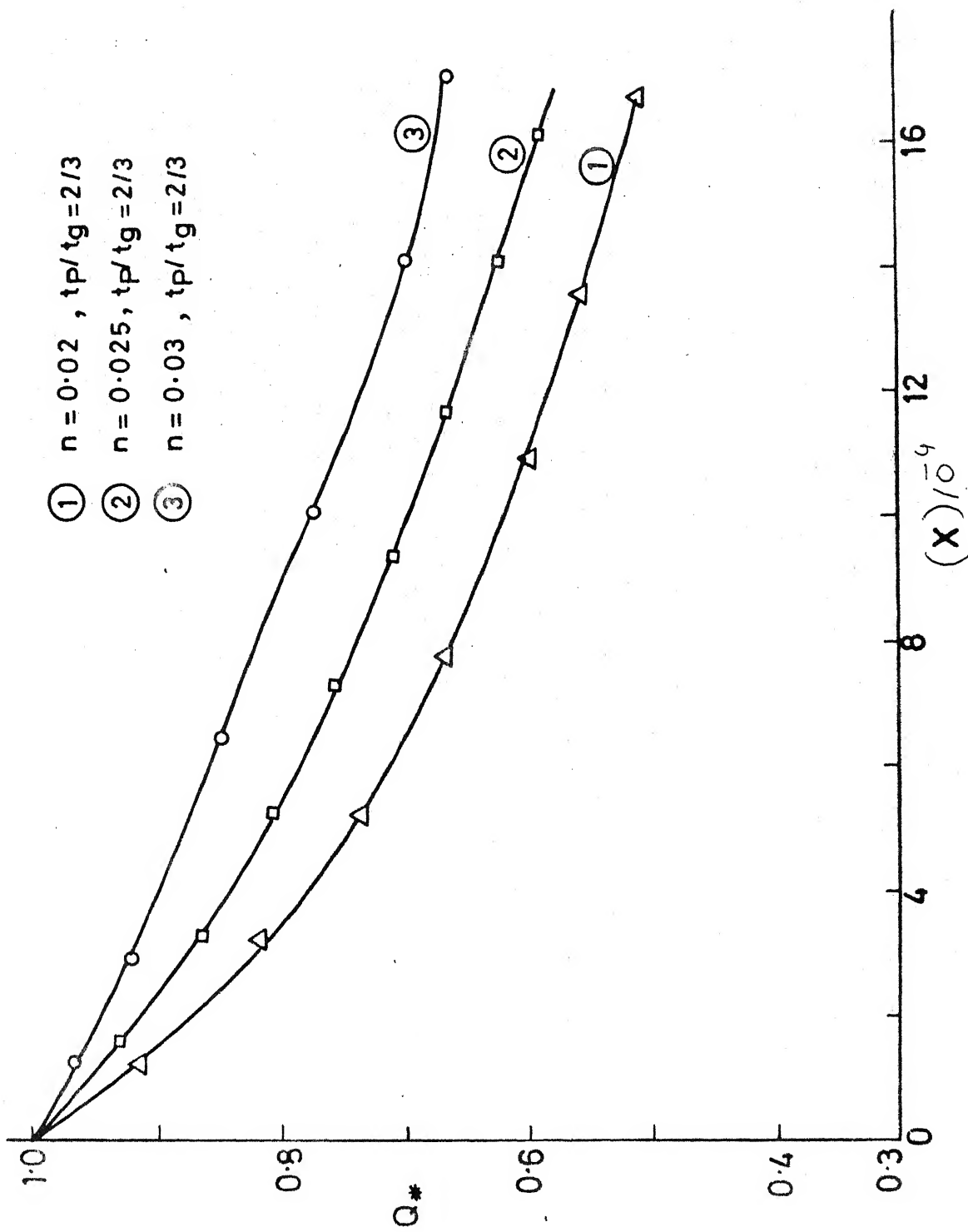
FIG.5.4 EFFECT OF n ON Q_*

$$\frac{T_P}{T_g} = \frac{1}{3}$$

① $n = 0.02$, $Y_w = 0.5$ ④ $n = 0.02$, $Y_w = 1$ ⑦ $n = 0.02$, $Y_w = 1.5$

② $n = 0.025$, $Y_w = 0.5$ ⑤ $n = 0.025$, $Y_w = 1$ ⑧ $n = 0.025$, $Y_w = 1.5$

③ $n = 0.03$, $Y_w = 0.5$ ⑥ $n = 0.03$, $Y_w = 1$

$(X)10^{-4}$
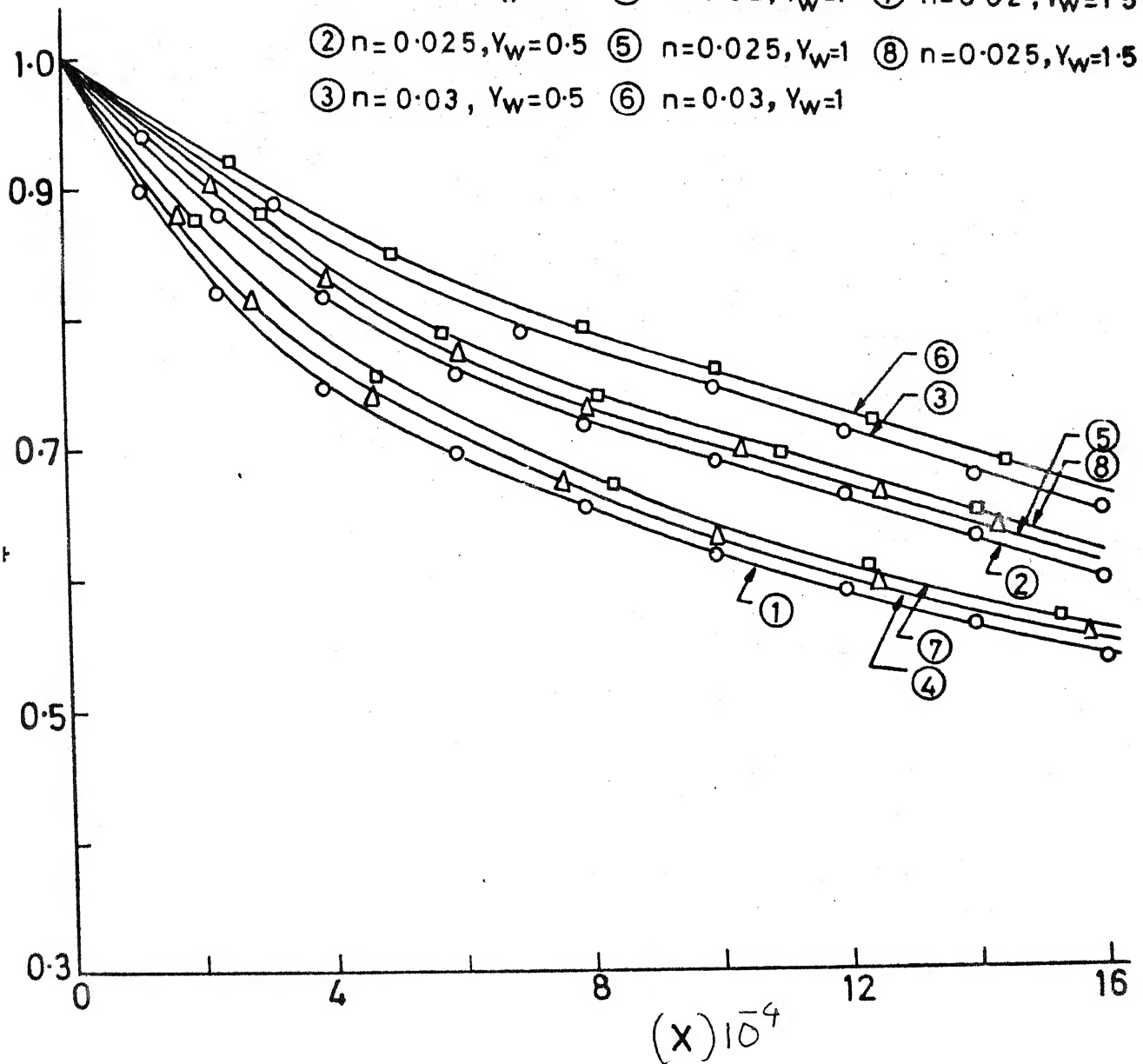
FIG. 5.5   EFFECT OF n AND Y_w ON SUBSIDENCE OF FLOOD WAVE
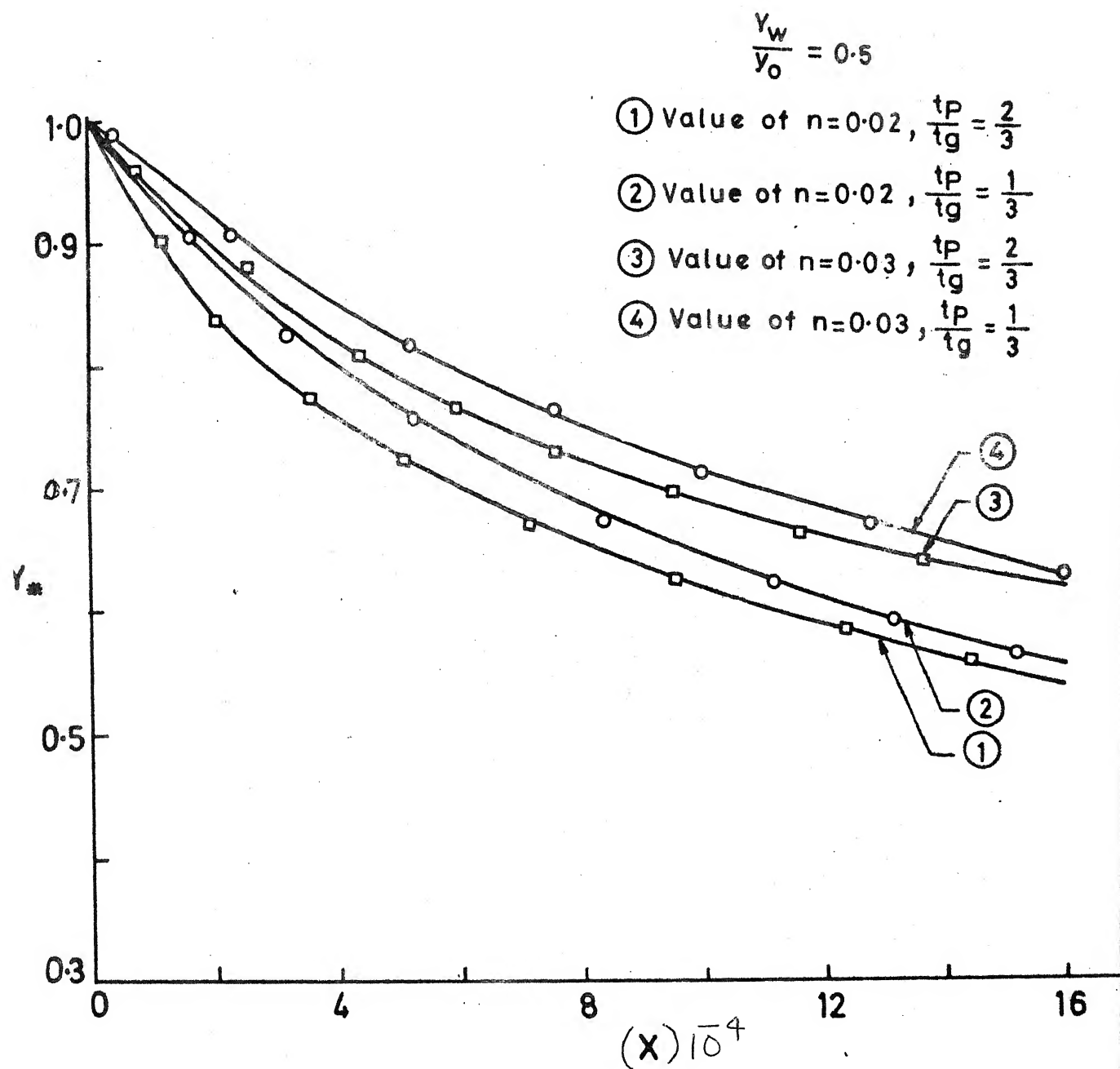
FIG. 5·6   EFFECT OF n AND t_P/t_g ON SUBSIDENCE OF FLOOD WAVE
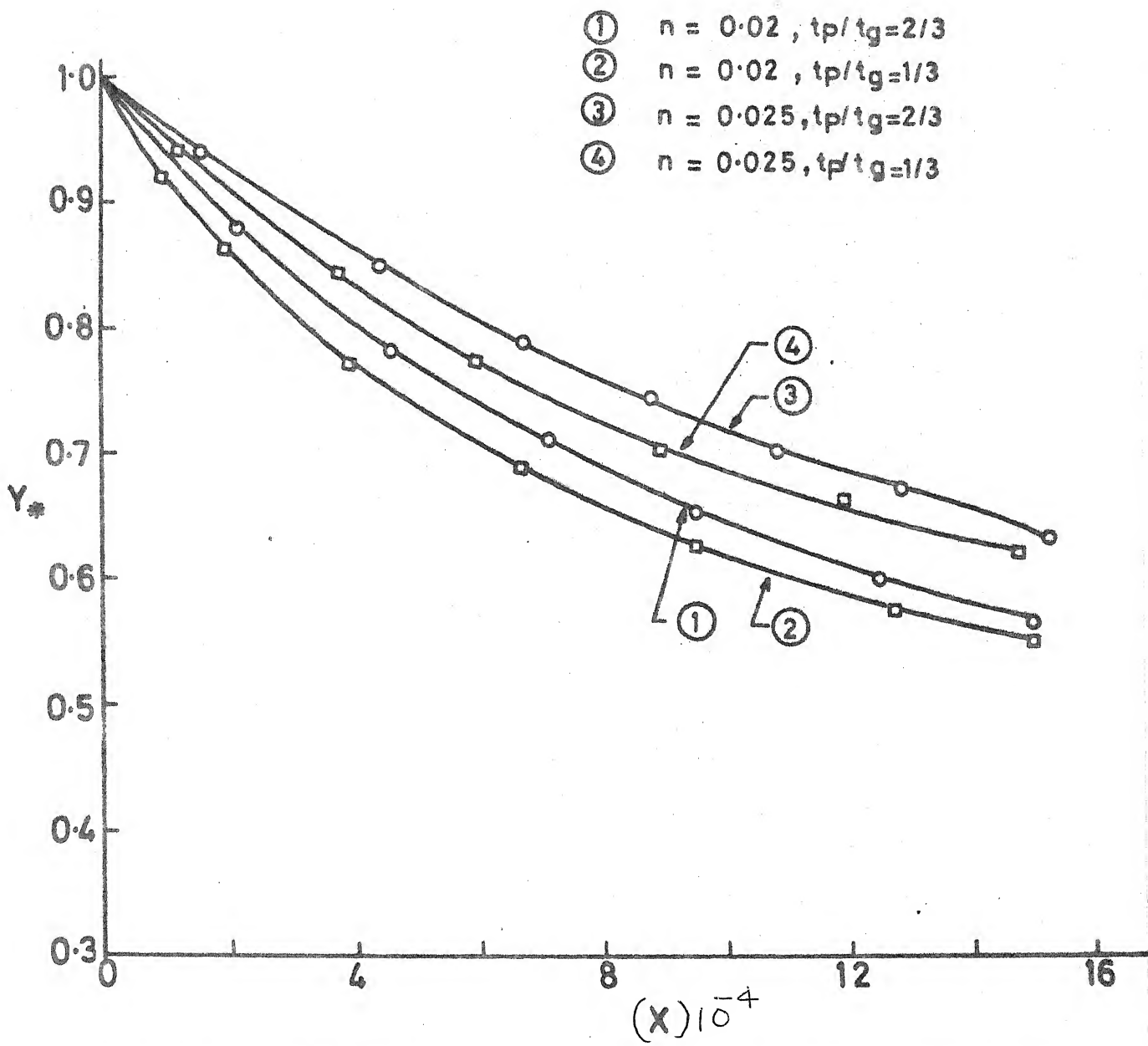
FIG. 5·7   EFFECT OF n AND t_p/t_g ON SUBSIDENCE
OF FLOOD WAVE

$$X = x/y_0$$

$$Y_* = \frac{(y_P)_i - (y_0)_{x=0}}{(y_{max})_{x=0} - (y_0)_{x=0}}$$

$$n = 0.02, \quad F_0 = 0.3, \quad \frac{y_P}{y_0} = 2, \quad \frac{t_P}{t_g} = \frac{1}{1.5}$$

① Value of $\dfrac{y_P - y_0}{t_P \times 3600} = 9.71 \times 10^{-5}$

② „ „ „ $= 7.51 \times 10^{-5}$
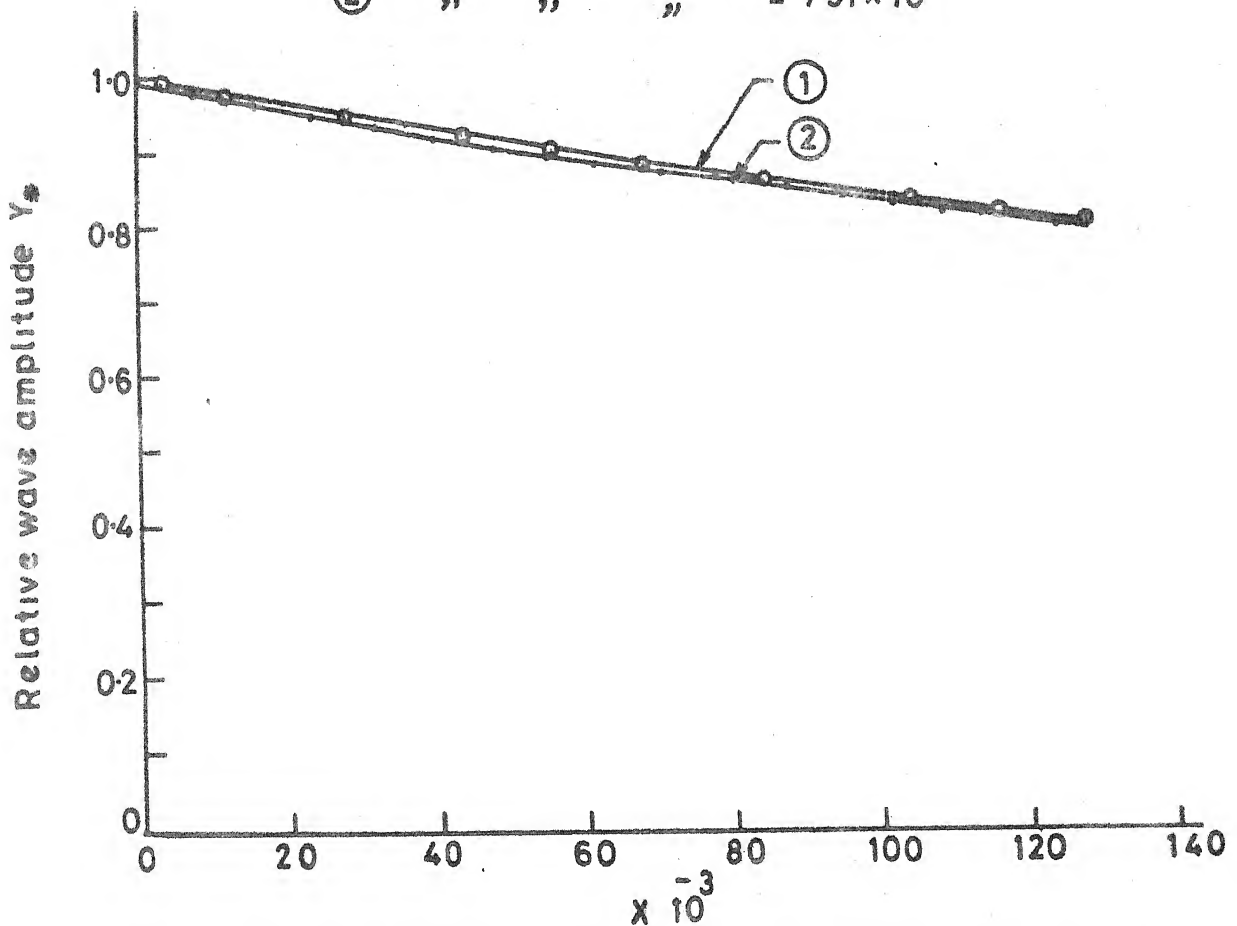
FIG. 5.8 EFFECT OF RATE OF RISE OF HYDROGRA[PH]
ON FLOOD WAVE SUBSIDENCE

$F_0 = 0.3, n = 0.02, \dfrac{t_P}{t_g} = \dfrac{2}{3}$

① POSITIVELY SKEWED HYDROGRAPH
② TRIANGULAR HYDROGRAPH

Relative wave amplitude, y_*
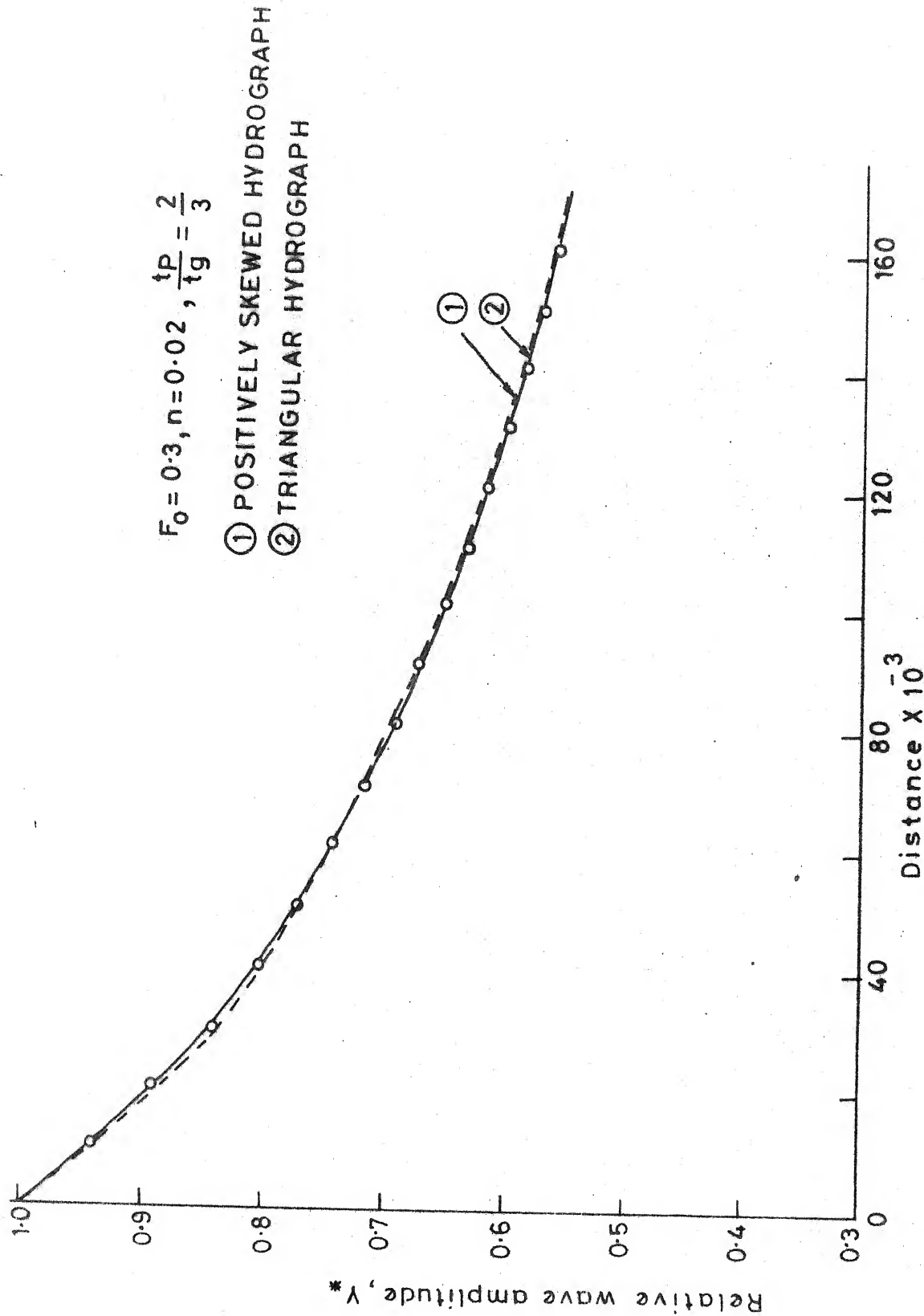
Distance $\times 10^{-3}$

FIG.5.9   EFFECT OF SHAPE OF THE HYDROGRAPH
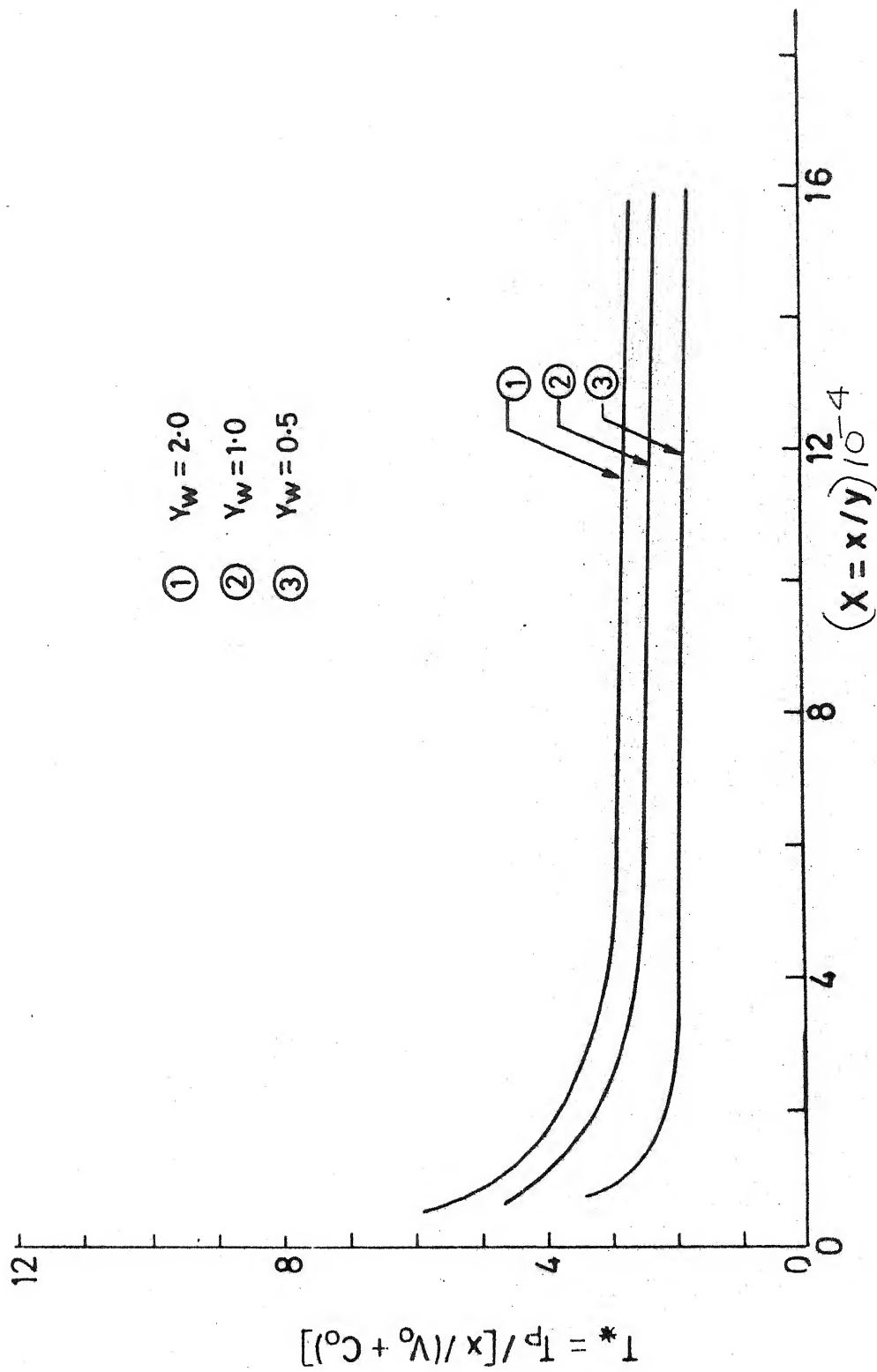
FIG. 5.10 EFFECT OF AMPLITUDE OF FLOOD WAVE ON THE TRAVEL
TIME FOR $T_P / T_g = 1/3$

Legend:
- ① $Y_w = 2 \cdot 0$
- ② $Y_w = 1 \cdot 0$
- ③ $Y_w = 0 \cdot 5$

Vertical axis: $T_* = T_p / [x / (V_o + C_o)]$

Horizontal axis: $(X = x/y) \, 10^{-4}$
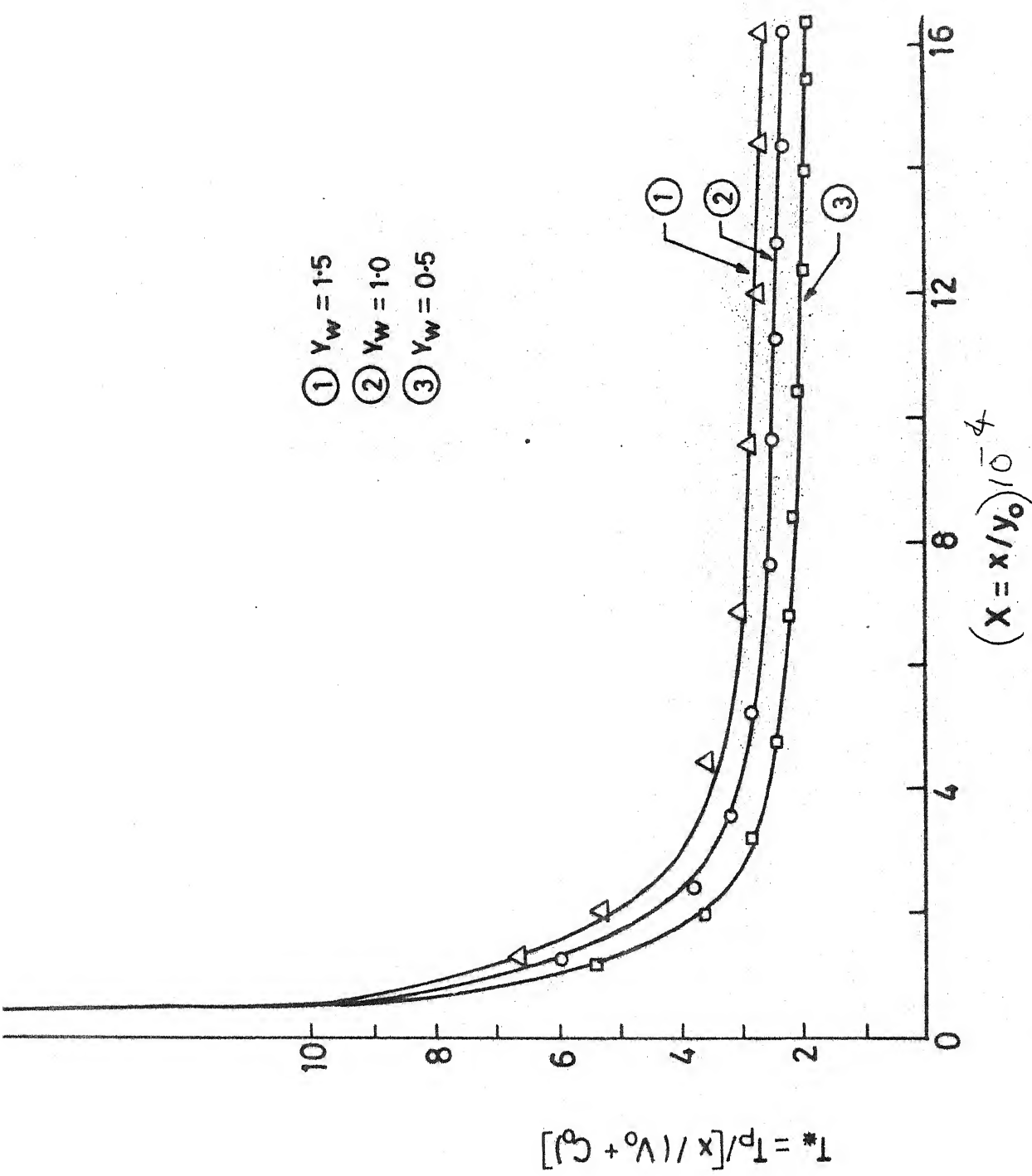
FIG. 5·11   EFFECT OF AMPLITUDE OF FLOOD WAVE ON
TRAVEL TIME FOR $T_p / T_a = 2/3$
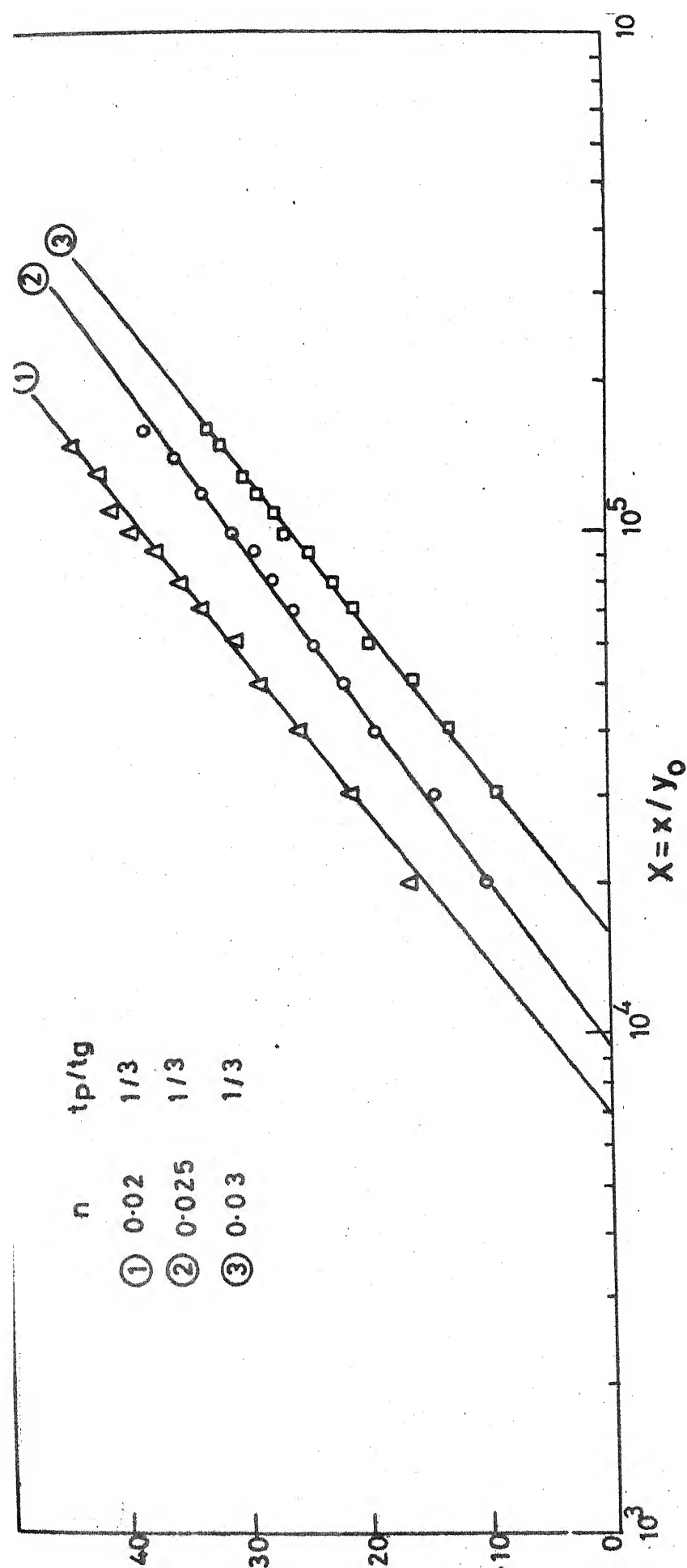
FIG·6·1a SUBSIDENCE OF FLOOD WAVE WITH DISTANCE
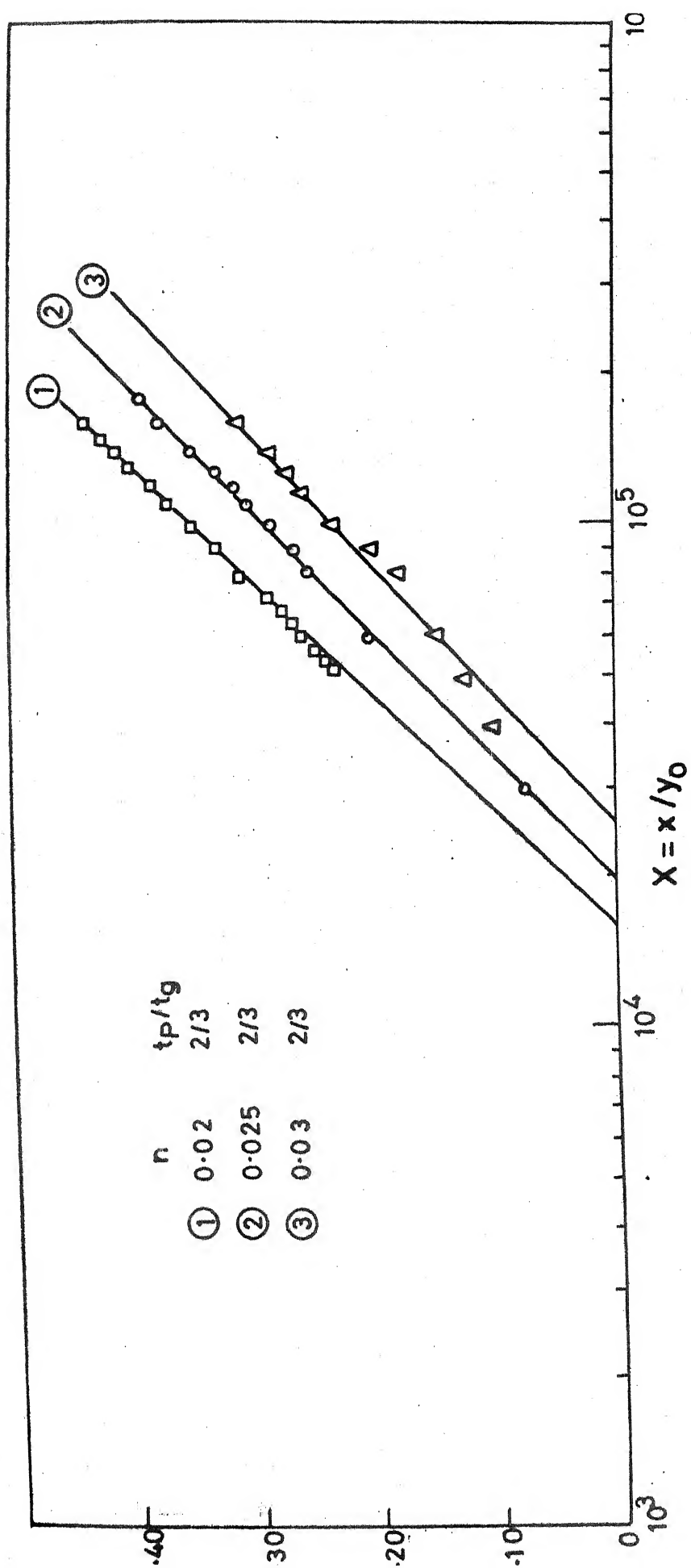
FIG.6·1b SUBSIDENCE OF FLOOD WAVE WITH DISTANCE

	n	t_p/t_g
①	0·02	2/3
②	0·025	2/3
③	0·03	2/3

$X = x/y_o$
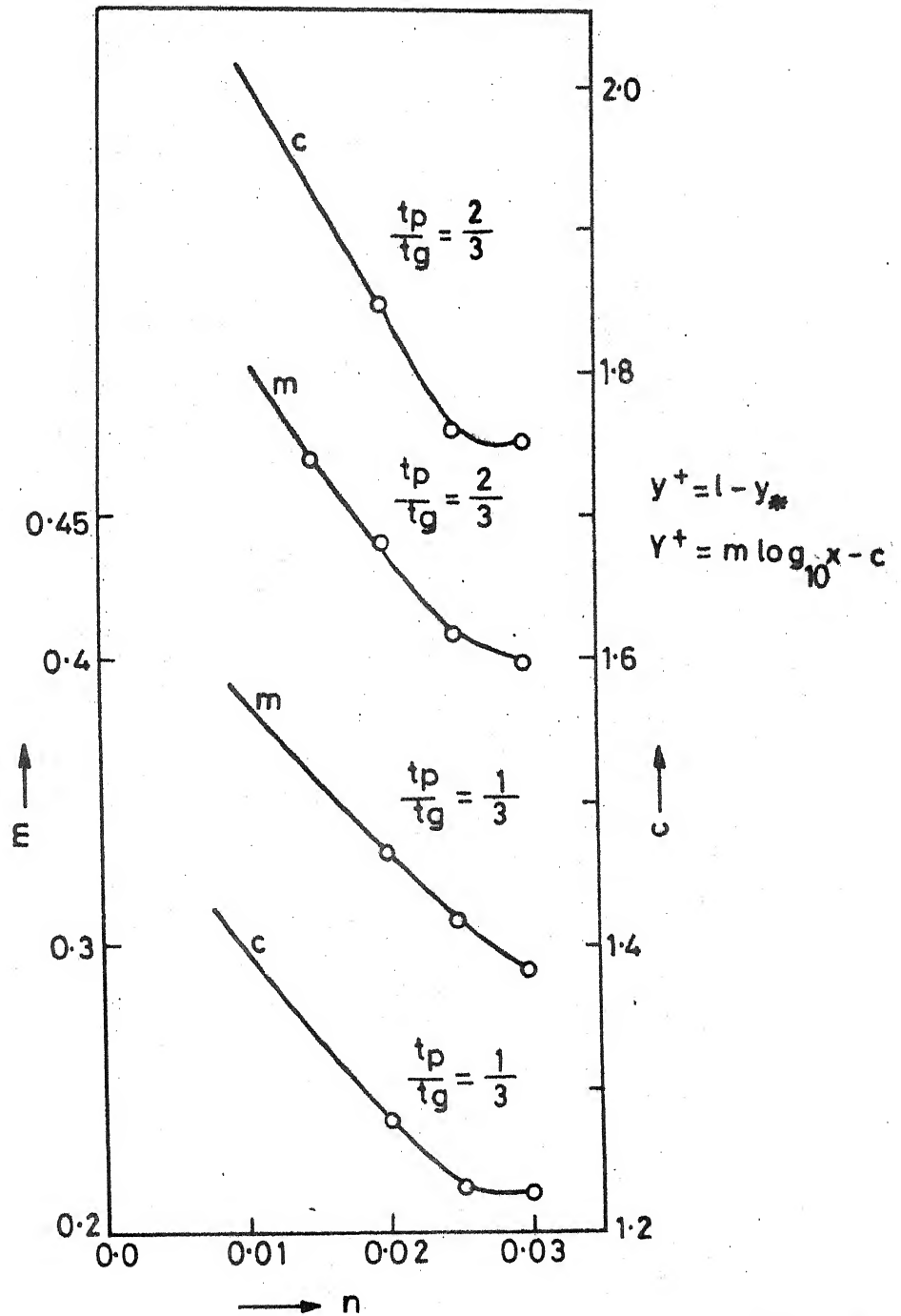
FIG. 6·2   EMPIRICAL CONSTANTS IN THE EQUATION
FOR THE DETERMINATION OF FLOOD WAVE
SUBSIDENCE
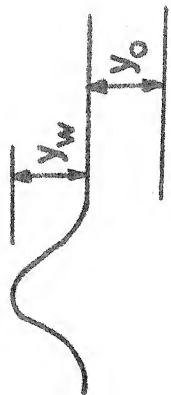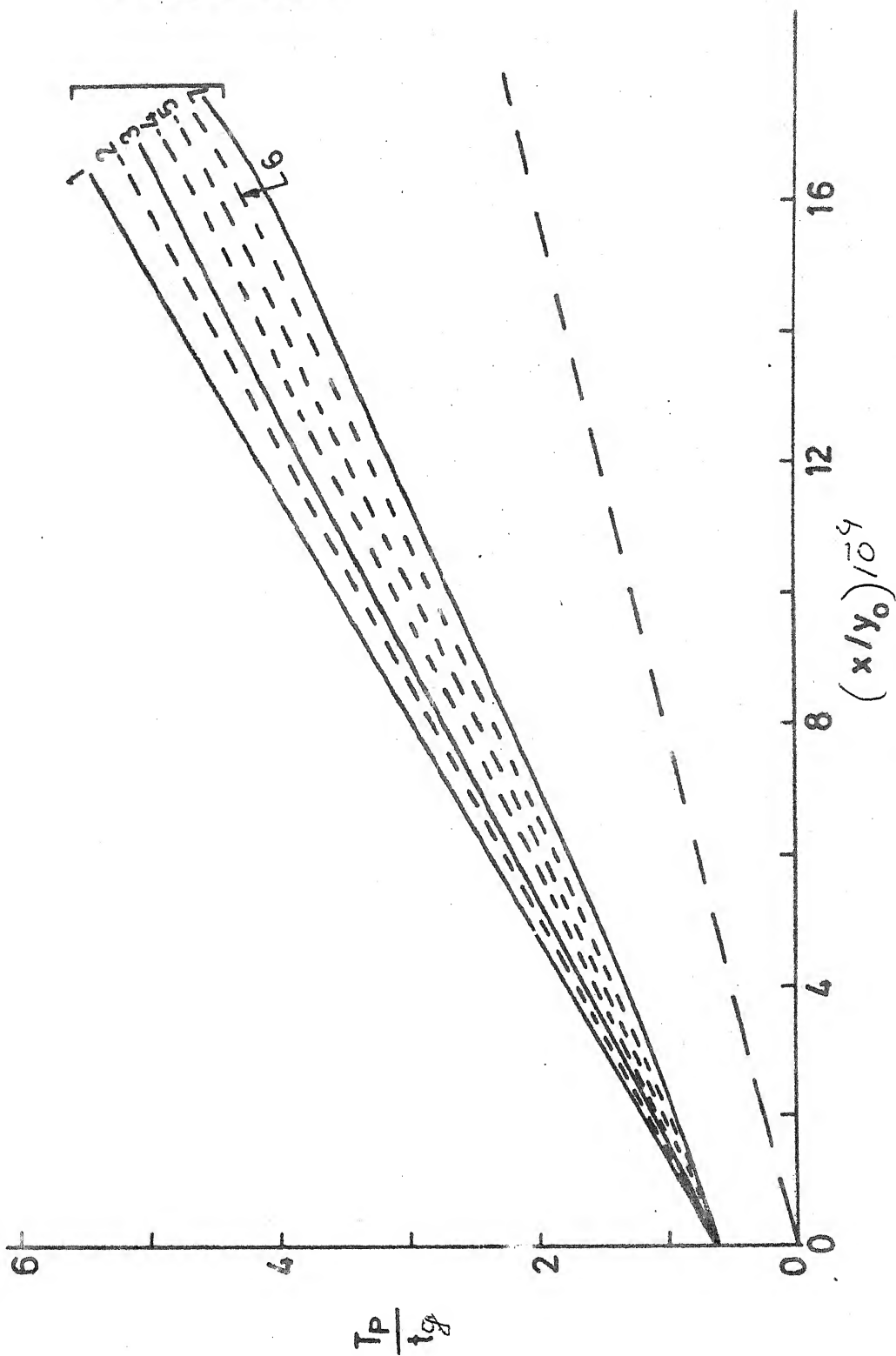
FIG. 6.3 TIME OF OCCURENCE OF FLOOD PEAK VERSUS DISTANCE

FLOW CHARTS

IMPLICIT METHOD OF FLOOD ROUTING
THROUGH IRREGULAR CHANNEL SYSTEMS

FLOW CHART

Main Program

```
        ┌─────────┐
        │  Start  │
        └─────────┘
             │
             ▼
┌──────────────────────────────────┐
│ Read                             │
│ M,N,L,dx,dT,TFIN,SO,G,Tzero      │
│ Xzero,t_g,t_p,t_p,y_o,dishi      │
└──────────────────────────────────┘
             │
             ▼
┌──────────────────────────────────┐
│ Stage (I)=f(t)                   │
│ I=1, MN                          │
└──────────────────────────────────┘
             │
             ▼
┌──────────────────────────────────┐
│ YIN(I) dishI / AR(y_o)           │
└──────────────────────────────────┘
             │
             ▼
┌──────────────────────────────────┐
│ EY(I)=YIN(I)                     │
│     I =I,N                       │
└──────────────────────────────────┘
             │
             ▼
┌──────────────────────────────────┐
│ T(K+1)=T(K)+dT                   │
│     K =1,MN                      │
└──────────────────────────────────┘
             │
    60       ▼
┌──────────────────────────────────┐
│ Call UBSTR                       │
└──────────────────────────────────┘
             │
             ▼
┌──────────────────────────────────┐
│ Call Inter                       │
└──────────────────────────────────┘
             │
             ▼
┌──────────────────────────────────┐
│ Call Dwns                        │
└──────────────────────────────────┘
             │
             ▼
┌──────────────────────────────────┐
│ Set Coefficients of the          │
│ matrix and Residual              │
│ Vectors                          │
└──────────────────────────────────┘
             │
             ▼
┌──────────────────────────────────┐
│ Call INVER                       │
└──────────────────────────────────┘
             │
             ▼
┌──────────────────────────────────┐
│ Compute Error in Trial           │
│ Values and Computer Values       │
└──────────────────────────────────┘
             │
             ▼
          ┌─────┐
          │  A  │
          └─────┘
```

Right column:

```
          ┌─────┐
          │  A  │
          └─────┘
             │
Go to 60     ▼
   ◄──── ◇─────────────┐
   +ve   │ If error    │
         │ tolerance   │
         └─────────────┘
             │ O OR -VE
             ▼
┌──────────────────────────────────┐
│ Type depth,                      │
│ time,discharge,                  │
│ velocity                         │
└──────────────────────────────────┘
             │
             ▼
┌──────────────────────────────────┐
│ Calculate new                    │
│ trial values of                  │
│ Vel. and depth                   │
│ for next time step               │
└──────────────────────────────────┘
             │
             ▼
┌──────────────────────────────────┐
│ Redefine vel. and                │
│ depth.                           │
└──────────────────────────────────┘
             │
             ▼
┌──────────────────────────────────┐
│ Time = time+ Dt                  │
└──────────────────────────────────┘
             │
Go to 60     ▼
   ◄──── ◇─────────────┐
   NO    │ If          │
         │ time > final│
         │ time        │
         └─────────────┘
             │ Yes
             ▼
          ┌─────────┐
          │  Stop   │
          └─────────┘
```

```
┌─────────────────────────┐
│  Subroutine UPSTR       │
└─────────────────────────┘
             │
             ▼
┌─────────────────────────┐
│ Calculation of          │
│ vel. and depth at       │
│ the upstream boun-      │
│ dary                    │
└─────────────────────────┘
             │
             ▼
┌─────────────────────────┐
│ Set all coefficients    │
│ of the matrix to        │
│ zero                    │
└─────────────────────────┘
             │
             ▼
┌─────────────────────────┐
│ Set the depth to        │
│ stage (K)               │
│ K = 1, M                │
└─────────────────────────┘
             │
             ▼
┌─────────────────────────┐
│ Call ..... INVER        │
└─────────────────────────┘
             │
             ▼
┌─────────────────────────┐
│ Reset the coeff-        │
│ icients of              │
│ matrix                  │
└─────────────────────────┘
             │
             ▼
      ┌──────────────┐
      │   Return     │
      └──────────────┘
```

```
┌─────────────────────────┐          ┌─────────────────────────────┐
│ Subroutine INTER        │          │ Subroutine INVER            │
└─────────────────────────┘          └─────────────────────────────┘
            │                                     │
            ▼                                     ▼
┌─────────────────────────┐          ┌─────────────────────────────┐
│ Calculation of vel.and  │          │ Redefine depth and vel.     │
│ depth at all distance   │          │ at all 4 points of a        │
│ points                  │          │ grid system for all the     │
└─────────────────────────┘          │ distance steps              │
            │                        └─────────────────────────────┘
            ▼                                     │
┌─────────────────────────┐                       ▼
│ DO I = 2, NN            │          ┌─────────────────────────────┐
│ Call      INVER         │          │ Calculate A,B and n at      │
└─────────────────────────┘          │ all distance steps          │
            │                        └─────────────────────────────┘
            ▼                                     │
┌─────────────────────────┐                       ▼
│ Set the coeff.          │          ┌─────────────────────────────┐
│ of the matrix           │          │ Calculate the average       │
└─────────────────────────┘          │ values of n and the         │
            │                        │ first and 2nd derivati-     │
            ▼                        │ ves of A and B              │
      ┌───────────┐                  └─────────────────────────────┘
      │ Return    │                                │
      └───────────┘                                ▼
                                     ┌─────────────────────────────┐
                                     │ Calculate the coeffs.       │
┌─────────────────────────┐          │ of the partial deri-        │
│ Subroutine DOWC         │          │ vatives                     │
└─────────────────────────┘          └─────────────────────────────┘
            │                                     │
            ▼                                     ▼
┌─────────────────────────┐          ┌─────────────────────────────┐
│ Calculation of vel. and │          │ Calculate the values of     │
│ depth at downstream     │          │ the coeff. at the Kth       │
│ point                   │          │ cycle                       │
└─────────────────────────┘          └─────────────────────────────┘
            │                                     │
            ▼                                     ▼
┌─────────────────────────┐          ┌─────────────────────────────┐
│ Compute the coefficients│          │ Calculate the values of     │
│ of the partial derivatives│        │ the residual vectors        │
└─────────────────────────┘          └─────────────────────────────┘
            │                                     │
            ▼                                     ▼
┌─────────────────────────┐          ┌─────────────────────────────┐
│ Set the coeff.          │          │ Repeat computation          │
│ of the matrix.          │          │ for all I,I=2,NI            │
└─────────────────────────┘          └─────────────────────────────┘
            │                                     │
            ▼                                     ▼
      ┌───────────┐                        ┌───────────┐
      │ Return    │                        │ Return    │
      └───────────┘                        └───────────┘
```

APPENDIX

IMPLICIT METHOD OF FLOOD ROUTING FOR PARAMETRIC STUDY IN A
RECTANGULAR CHANNEL

```
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
     TERMS ARE EXPLAINED HERE
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
A(I,J)    =MATRIX OF COEFFIENTS
DELX      =INCRIMENT OF DISTANCE IN KILOMETERS
G         =GRAVITATIONAL CONSTANTS
XFIN      =FINAL TIME
TAVER     =A SUBROUTINE FOR SOLVING THE BANDED MATRIX
DISHI     =INITIAL DIS. AT U/S END IN CUBIC METERS/SEC.
DISHO     =INITIAL DIS. AT D/S END IN CUBIC METERS/SEC.
SQ        =LATERAL INFLOW IN CUBIC METERS/SEC.PER METER LENGTH
DI        =INITIAL DEPTH AT U/S END IN METERS
DN        =INITIAL DEPTH AT D/S END IN METERS
NU        =NO. OF EQUATIONS AND NO. OF UNKNOWNS
TIME      =TIME AT ANY INSTANT IN HOURS.
T(K)      =VALUE OF T ON T-AXIS AT EACH GIVEN POINT OF MN IN HOURS
C(K)      =VECTOR OF RESIDUES
SO        =CHANNEL BOTTOM SLOPE
DIST(K)   =DISTANCE FOR EACH GRID POINTS FROM X=0 IN KMS.
YIN(K)    =DEPTH AT T=J
VIN(K)    =VELOCTY AT T=J
EV(K)     =VELOCTY AT T=J+1
X(K)      =VECTOR OF NEW TRIAL VALUES
STAGE(K)  =INPUT HYDROGRAPH GIVEN IN DTIME,IN METERS
DG(K)     =INTERPOLATION FUNCTION IN TERMS OF DISTANCE
DISCH(K)  =DISCHARGE IN CUBIC METERS/SEC.
EA(K)     =AREA AT EACH GRID POINT BASED ON DEPTH.IN SQ.METERS
O(K)      =LATERAL INFLOW =SO
EQ(K)     =DISCHARGE   AT EACH GRID POINT BASED ON DEPTH IN M/SEC.
MN        =NO. OF POINTS GIVEN ON T-AXIS
N         =NO. OF POINTS GIVEN ON X-AXIS
L         =INDEX FOR CURRENT VALUE ON THE T-AXIS
TZERO     =INITIAL TIME IN HOURS
DTIME     =TIME INTERVAL BETWEEN DISCRETE POINTS ON T-AXIS
XZERO     =INITIAL DISTANCE IN KMS.
AR        =X-SECTIONAL AREA EQUIATIONS
BR        =TOP WIDTH FUNCTION
DAY       =FIRST DERIVATIVE OF AREA W.R.T DEPTH Y
DDAY      =SECOND DERIVATIVE OF AREA FUNCTION
DBY       =FIRST DERIVATIVE OF TOP WIDTH
YO        =INITIAL STEADY FLOW DEPTH
YW        =INITIAL WAVE AMPLITUDE
TG        =TIME TO THE CENTRE OF GRAVITY OF THE HYDROGRAPH
      TP       =TIME TO OCCURRENCE OF PEAK IN THE INFLOW HYDROGRAPH

                MAIN PROGRAMME

      COMMON/ABLOK/Z(150),DIST(150),YIN(150),VIN(150),EV(150),EY(150),
2DG(150),DISCH(150),T(150),VT(150),YT(150),Q(150),EQ(150),
3DY(150),DV(150),STAGE(150),EA(150)
      COMMON/BBLOK/G,DTIME,SO,DIDX,DXDT,DX,DT,TIME,DR1,DR2,S,R,
2V,U,DR1DU,DR1DV,DR1DS,DR1DT,DR2DU,DR2DV,DR2DS,DR2DT
      COMMON/CBLOK/MN,M,L,NL,MC,I,MM
      COMMON/DBLOK/SO,ELEVO,ELEVN,XFIN,DELX,DELT,XZERO,DFIN
      COMMON/FBLOK/A(265,265),C1(265),C(265),X(265)
      DIMENSION B(31,31)
      TYPE 1
      OPEN(UNIT=21,FILE='NEW.CDR')
          INITIAL DATA
          ------------
```

aQa@a@a9a9a@a@a@a@a@a@a@a@a@a@a@a@
THIS PROGRAMME IS WITH THETA=0.5.
aa@a@a@a@a@a@a@a@a@a@a@a@a@a@a@a@

```
      IP=0.0
      READ(21,*),MM,N,L
      READ(21,*),TFIN,TZERO,G,DTIME,XZERO,DISHI,DISHN,
     2DELX,XFIN,DELT,YW,YO,SO,TP,TG
      DO 10 I=1,N
10    STAGE(I)=YO+YW*EXP(-((2*(I-1))-TP)/(TG-TP))*(((2*(I-1)))/TP)**
     1(TP/(TG-TP))
      TYPE 29,(STAGE(K),K=1,MN)
29    FORMAT(5X,'INFLOW HYDROGRAPH IS',/5X,20F6.2/10F6.2)
      DN           =YO
      DI           =STAGE(1)
      VI           =DISHI/AR(DI)
      VM           =DISHN/AR(DN)
      SO           =(DISHN-DISHI)/(XFIN*1000.0)
      TYPE 9
9     FORMAT(3X,'INFLOW HYDROGRAPH IS LOGPEARSON TYPE 3',/3X,42(1H-))
      CI=CI(DI)
      TYPE 7,SO,DISHI,YO,YW,TG,CI,TP
7     FORMAT(5X,'SLOPE= ',F15.7,'YO= ',F5.2,'YO= ',F5.2,'YW= ',F5.2,
     2' TG= ',F5.2,'MANNING''S N=',E15.7,'TP= ',F5.2,/5X,80(1H-))
      TYPE 29
29    FORMAT(/70(1H))
      TYPE 21
      MM           =MN-1
      NU           =2*N-1
      NN           =N-1
      T(1)         =TZERO
      DIST(1)      =0.0
      IRAY=1
      DO 30 I      =1,NM
      DIST(I+1)    =DIST(I)+DELX
30    CONTINUE
      DT=DELT*60.0*60.0
      DX           =DELX*1000.0
      DTDX         =DT/DX
      DXDT         =DX/DT
      TIME         =TZERO
      DO 50 I      =1,N
      DG(I)        =(DIST(I)-XZERO)/(XFIN-XZERO)
      VIN(I)       =VI+(VM-VI)*DG(I)
      YIN(I)       =DI+(DN-DI)*DG(I)
      TYPE 39,I,VIN(I),I,YIN(I),I,DG(I)
39    FORMAT(/,5X,'VIN(',I3,')=',F10.4,5X,'YIN(',I3,')=',F10.4,
     25X,'DG(',I3,')=',F10.4)
      EV(I)        =VIN(I)
      EI(I)        =YIN(I)
      DISCH(I)     =DISHI+(DISHN-DISHI)*DG(I)
      Q(I)         =SO
50    CONTINUE
      DO 60 K      =1,MM
60    T(K+1)       =T(K)+DTIME
      TIME         =TIME+DELT
65    CALL UPSTR
      CALL INTER
      CALL DWNS
      DO 180 I     =1,NL
180   CI(I)        =C(I)
13    FORMAT(1X,16F5.1)
      DO 177 N=1,NL
      DO 177 J=1,NL
177   B(N,J)=A(N,J)
      CALL INVER(B,C1,NL,KS)
      DO 190 I     =1,NL
      X(I)         =C1(I)
190   CONTINUE
      DO 200 I     =1,N
      VI(I)        =EV(I)
```

```
200 YT(I)        =EY(I)
    K            =NL-1
    DO 210 J     =1,K,2
    I            =(J+1)/2
    EV(I)        =X(J)
210 EY(I+1)      =X(J+1)
    EV(N)        =X(NL)
    ITRAY=ITRAY+1
    IF(ITRAY-50)330,330,335
335 TYPE 333,ITRAY,EY(1),EY(N),EV(1),EV(N)
333 FORMAT(1H ,12,4E11.3)
    CALL EXIT
330 CONTINUE
    DO 240 I     =1,N
    ERROR        =(EV(I)-VT(I))/EV(I)*100.0
    IF(ABS(ERROR)-2.0) 240,240,65
240 CONTINUE
    IF(IP-TIME) 245,245,255
245 CONTINUE
    IP=IP+2.0
    TYPE 31,TIME
    TYPE 23
31  FORMAT(5X,F7.2)
    DO 250 I     =1,N
    EA(I)=AR(EY(I))
    EQ(I)=EA(I)*EV(I)
250 TYPE 25,DIST(I),EY(I),EQ(I)
    DO 260 I     =1,N
255 CONTINUE
    ITRAY=1
    DY(I)        =EY(I)-YIN(I)
260 DV(I)        =EV(I)-VIN(I)
    DO 270 I     =1,N
    YIN(I)       =EY(I)
270 VIN(I)       =EV(I)
    TIME         =TIME+DELT
    IF(2-TIME) 300,280,280
280 DO 285 I     =1,N
    EY(I)        =EY(I)+DY(I)*.5
285 EV(I)        =EV(I)+DV(I)*.5
    GO TO 65
1   FORMAT(35X,'STREAMFLOW ROUTING BY IMPLICIT METHOD'/33X,
    241(1H*))
12  FORMAT(5X,11(2X,F9.4))
21  FORMAT(15X,'VALUES OF THE VARIABLES')
23  FORMAT(6X,'DISTANCE',3X,'DEPTH',5X,'DISCHARGE')
25  FORMAT(6X,F6.1,4X,F5.2,4X,F10.3)
300 CALL EXIT
    END
C
      SUBROUTINE OPSTR
C     --------------------------
      COMMON/ABLOK/Z(150),DIST(150),YIN(150),VIN(150),EV(150),EY(150
     2OG(150),DISCH(150),T(150),VT(150),YT(150),Q(150),EQ(150),
     3DY(150),DV(150),STAGE(150),EA(150)
      COMMON/BBLOK/G,DTIME,SQ,DYDX,DXDT,DX,DT,TIME,DR1,DR2,S,R,
     2V,U,DR1DU,DR1DV,DR1DS,DF1DT,DR2DU,DR2DV,DR2DS,DR2DT
      COMMON/CBLOK/NN,N,L,NL,MN,I,MM
      COMMON/DBLOK/SO,ELEVO,ELEVN,XFIN,DELX,DELT,XZERO,DFIN
      COMMON/FBLOK/A(265,265),C1(265),C(265),X(265)
C
      COMPUTATION AT U/S BOUNDARY
C     --------------------------
65  DO 70 I      =1,NL
    X(I)         =0.0
    DO 70 J      =1,NL
70  A(I,J)       =0.0
```

```
      IF(TIME-T(L)) 74,71,72
71    SURFL       =STAGE(L)
      GO TO 80
72    L           =L+1
74    SURFL       =STAGE(L-1)+(TIME-T(L-1))*(STAGE(L)-STAGE(L-1))/DTIME
80    EY(1)       =SURFL
      I           =1
      CALL INVER
      A(1,1)      =DR1DU
      A(1,2)      =DR1DT
      A(1,3)      =DR1DV
      A(2,1)      =DR2DU
      A(2,2)      =DR2DT
      A(2,3)      =DR2DV
C     TYPE 14,DR1DU,DR1DT,DR1DV,DR2DU,DR2DT,DR2DV
14    FORMAT(2X,'A(1,1)='1X,F5.2,1X,'A(1,2)=',1X,F5.2,1X,'A(1,3)=',1X,
     1F5.2,'A(2,1)='F5.2,'A(2,2)='F5.2,2X,'A(2,3)='F5.2/80(1H-))
      C(1)        =DR1DU*U+DR1DV*V+DR1DT*R-DR1
      C(2)        =DR2DU*U+DR2DV*V+DR2DT*R-DR2
C     TYPE 24,C(1),C(2)
24    FORMAT(3X,'C(1)=',F5.1,2X,'C(2)=',F5.1/20(1H-))
      RETURN
      END
C
C           SUBROUTINE INTER
C           ------------------
      COMMON/ABLOK/Z(150),DIST(150),YIN(150),VIN(150),EV(150),EY(150)
     2DG(150),DISCH(150),T(150),VI(150),YT(150),Q(150),EQ(150),
     3DY(150),DV(150),STAGE(150),EA(150)
      COMMON/BBLOK/G,DTIME,SQ,DTDX,DXDT,DX,DT,TIME,DR1,DR2,S,R,
     2V,U,DR1DU,DR1DV,DR1DS,DR1DT,DR2DU,DR2DV,DR2DS,DR2DT
      COMMON/CBLOK/ND,N,L,NL,MN,I,MM
      COMMON/DBLOK/SO,ELEVO,ELEVN,XFIN,DELX,DELT,XZERO,DFIN
      COMMON/FBLOK/A(265,265),CI(265),C(265),X(265)
      TYPE 11
11    FORMAT(5X,'C(M),C(M+1),A(M,J),A(M,J+1),A(M,J+2),A(M,J+3),
     1A(M+1,J),A(M+1,J+1),A(M+1,J+2),A(M+1,J+3) ARE AS FOLLOWS')
C           COMPUTATION AT INTERIOR POINTS
C           -------------------------------
100   DO 150 I    =2,MN
      CALL INVER
      J           =2*I-2
      M           =2*I-1
      A(M,J)      =DR1DS
      A(M,J+1)    =DR1DU
      A(M,J+2)    =DR1DT
      A(M,J+3)    =DR1DV
      A(M+1,J)    =DR2DS
      A(M+1,J+1)  =DR2DU
      A(M+1,J+2)  =DR2DT
      A(M+1,J+3)  =DR2DV
      C(M)        =DR1DU*U+DR1DV*V+DR1DT*R-DR1+DR1DS*S
      C(M+1)      =DR2DU*U+DR2DV*V+DR2DT*R-DR2+DR2DS*S
      TYPE 23,C(M),C(M+1)
23    FORMAT(2X,2F5.1/)
      TYPE 22,A(M,J),A(M,J+1),A(M,J+2),A(M,J+3),A(M+1,J),A(M+1,J+1),
     1A(M+1,J+2),A(M+1,J+3)
C     TYPE 11
22    FORMAT(2X,6F5.1)
150   CONTINUE
      RETURN
      END
C
C     THIS SUBROUTINE IS FOR CALCULATIONS AT DOWNSTREM BOUNDARY.
C
C           SUBROUTINE DWNS
C           -------------------
```

```
      COMMON/ABLOK/Z(150),DIST(150),YIN(150),VIN(150),EV(150),EY(150)
     2DG(150),DISCH(150),T(150),VT(150),YT(150),Q(150),EQ(150),
     3DY(150),DV(150),STAGE(150),EA(150)
      COMMON/BBLOK/G,DTIME,SO,DTDX,DXDT,DX,DT,TIME,DR1,DR2,S,R,
     2V,U,DR1DU,DR1DV,DR1DS,DR1DT,DR2DU,DR2DV,DR2DS,DR2DT
      COMMON/CBLOK/NN,N,L,NL,MN,I,MM
      COMMON/DBLOK/SO,ELEVO,ELEVN,XFIN,DELX,DELT,XZERO,DFIN
      COMMON/FBLOK/A(265,265),C1(265),C(265),X(265)

C         COMPUTATION AT O/S BOUNDARY
C         ---------------------------
      P         =EV(N)
      R         =EY(N)
      DADY      =DAY(R)
      V1        =P*P
      A1        =AR(R)
      A2        =A1*A1
      W         =P*A1
      CL=CI(R)
      DR1=R-5.0
      DR1DT=1.0
      DR1DV=0.0
      A(NL,NL-1)=DR1DT
      A(NL,NL) =DR1DV
      C(NL)    =DR1DT*R+DR1DV*P-DR1
      RETURN
      END
C$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
C     THIS SUBROUTINE CALCULATES THE COEFFICIENT AND RESIDUES
C$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
      SUBROUTINE INVER
C         ----------------
      COMMON/ABLOK/Z(150),DIST(150),YIN(150),VIN(150),EV(150),EY(150)
     2DG(150),DISCH(150),T(150),VT(150),YT(150),Q(150),EQ(150),
     3DY(150),DV(150),STAGE(150),EA(150)
      COMMON/BBLOK/G,DTIME,SO,DTDX,DXDT,DX,DT,TIME,DR1,DR2,S,R,
     2V,U,DR1DU,DR1DV,DR1DS,DR1DT,DR2DU,DR2DV,DR2DS,DR2DT
      COMMON/CBLOK/NN,N,L,NL,MN,I,MM
      COMMON/DBLOK/SO,ELEVO,ELEVO,XFIN,DELX,DELT,XZERO,DFIN
      COMMON/FBLOK/A(265,265),C1(265),C(265),X(265)

C         SOLUTION OF SYSTEM OF EQUATIONS WITH 4 NONZERO TERMS ON
C                     THE BANDED MATRIX
C         --------------------------------------------------------
      U         =EV(I)
      V         =EV(I+1)
      S         =EY(I)
      R         =EY(I+1)
      TYPE *,S,R
      TYPE 39
   39 FORMAT(10X,'S=    R= ')
      SB        =YIN(I)
      RB        =YIN(I+1)
      UB        =VIN(I)
      VB        =VIN(I+1)
      A1        =AR(S)
      A2        =AR(R)
      B1        =BR(S)
      B2        =BR(R)
      AB1       =AR(SB)
      AB2       =AR(RB)
      BB1       =BR(SB)
      BB2       =BR(RB)
      CB1       =CI(SB)+(CN(SB)-CI(SB))*DG(I)
      CB2       =CI(RB)+(CN(RB)-CI(RB))*DG(I+1)
      CI1       =CI(S)
      CN1       =CN(S)
```

```
CI2           =CI(R)
C+2           =CN(R)
CO1           =CI1+(CN1-CI(1)*DG(I)
CO2           =CI2+(CN2-CI2)*DG(I+1)
Q1            =Q(I)
Q2            =V(I+1)
DA1DY         =DAY(S)
DA2DY         =DAY(R)
DB1DY         =DBY(S)
DB2DY         =DBY(R)
DB3DY         =DDAY(S)
DB4DY         =DDAY(R)
DA3DY         =DAY(SB)
DA4DY         =DAY(RB)
V1            =V+VB-U-UB
V2            =V+U-VB-UB
Q1            =R-S+RB-SB
Q2            =R+S-SB-RB
VD            =V+U+VB+UB
E1            =DA1DY
E2            =DA2DY
EB1           =DA3DY
EB2           =DA4DY
QQ            =Q1*(U/A1+V/A2+UB/AB1+VB/AB2)
BD            =1./E1+1./E2+1./EB1+1./EB2
AD            =A1/E1+A2/E2+AB1/EB1+AB2/EB2
SF1           =CO1*CO1*U*ABS(U)*(S)**(-4.0/3.0)
SF2           =CO2*CO2*V*ABS(V)*(R)**(-4.0/3.0)
SF3           =CB1*CB1*UB*ABS(UB)*(SB)**(-4.0/3.0)
SF4           =CB2*CB2*VB*ABS(VB)*(RB)**(-4.0/3.0)
DSF1          =CO1*CO1*U*(S)**(-4.0/3.0)
DSF2          =CO2*CO2*V*R**(-4.0/3.0)
SF            =SF1+SF2+SF3+SF4
DB4           =DB1DY/E1
DB3           =DB3DY/(E1*E1)
DB2           =DB4DY/(E2*E2)
DB1           =DB2DY/E2
DA4           =DA1DY/A1
DA3           =DA1DY/(A1*A1)
DA2           =DA2DY/(A2*A2)
DA1           =DA2DY/A2
DR1           =.25*DTDX*VD*Q1+Q2+DTDX*.25*V1*AD-.5*Q1*DT*BD
DR2           =DTDX*V2/G+.25*VD*V1/G+.5*DX*QD/G+Q1-DX*2*SD+.5*DX*SF
W             =.25*DTDX
DR1DS         =1-W*VD+V1*(DA1DY/E1-A1*DB3)*W+.5*DT*DB3*Q1
DR1DT         =W*VD+1+W*V1*(DA2DY/E2-A2*DB2)+.5*DT*Q1*DB2
DR1DV         =.25*DTDX*D1+DTDX*AD*.25
DR1DU         =.25*DTDX*D1-DTDX*AD*.25
DR2DU         =(DXDT-.5*(U+UB)+.5*DX*Q1/A1)/G+DX*DSF1
DR2DV         =(DXDT+.5*(V+VB)+.5*DX*Q1/A2)/G+DX*DSF2
DR2DT         =1-.5*DX*Q1*V*DA2/G+DX*(4.0/3.0)*SF2*(DB1-DA1)*.5
DR2DS         =-1-.5*DX*Q1*U*DA3/G+DX*(4.0/3.0)*SF1*(DB4-DA4)*.5
RETURN
END
SUBROUTINE INVER (A,B,N,KS)
DIMENSION A(1),B(1)
FORWARD SOLUTION
TOL=0.0
KS=0
JJ=-N
DO 65 J=1,N
JY=J+1
JJ=JJ+N+1
BIGA=0.
IT=JJ-J
L1=J+4
IF(L1-N) 10,10,12
```

```
12      L1=N
10      DO 30 I=J,L1
C       SEARCH FOR MAXIMUM COEFFICIENT IN COLUMN
        IJ=II+1
        IF(ABS(BIGA)-ABS(A(IJ)))  20,30,30
20      BIGA=A(IJ)
        IMAX=I
30      CONTINUE
C       TEST FOR PIVOT LESS THAN TOLERANCE(SINGULAR MATRIX
32      IF(ABS(BIGA)-TOL) 35,35,40
35      KS=1
        RETURN
C       INTERCHANGE ROWS IF NECESSARY
40      I1=J+N*(J-2)
        IT=IMAX-J
        L2=J+4
        IF(L2-N) 42,42,44
44      L2=N
42      DO 50 K=J,L2
        I1=I1+N
        I2=I1+IT
        SAVE=A(I1)
        A(I1)=A(I2)
        A(I2)=SAVE
C       DIVIDE EQUATION BY LEADING COEFFICIENT
C       P 104
50      A(I1)=A(I1)/BIGA
52      SAVE=B(IMAX)
        B(IMAX)=B(J)
        B(J)=SAVE/BIGA
C       ELIMINATE NEXT VARIABLE
        IF(J-N) 55,70,55
55      IQS=N*(J-1)
        L3=JY+4
        IF(L3-N) 57,57,59
59      L3=N
57      DO 65 IX=JY,L3
        IXJ=IQS+IX
        IT=J-IX
        DO 60   JX=JY,L3
        IXJX=N*(JX-1)+IX
        JJX=IXJX+IT
60      A(IXJX)=A(IXJX)-(A(IXJ)*A(JJX))
65      B(IX)=B(IX)-(B(J)*A(IXJ))
C       BACK SOLUTION
70      NY=N-1
        IT=N**2
        DO 80 J=1,NY
        IA=IT-J
        IB=N-J
        IC=N
        DO 80 K=1,J
        B(IB)=B(IB)-A(IA)*B(IC)
        IA=IA-N
80      IC=IC-1
        RETURN
        END
C
C       THIS FUNCTION SUBPROGRAM RETURNS AREA AND OTHER VARIABLES.

        FUNCTION AR(Y)
        AR=Y
        RETURN
        END
        FUNCTION BR(Y)
        BR=1.0
        RETURN
```

```
END
FUNCTION CI(Y)
CI=0.02000
RETURN
END
FUNCTION CN(Y)
CN=0.02000
RETURN
END
FUNCTION DAY(Y)
DAY=1.0
RETURN
END
FUNCTION DBY(Y)
DBY=0.0
RETURN
END
FUNCTION DDAY(Y)
DDAY=0.0
RETURN
END
```

          STREAMFLOW ROUTING
       ****
INFLOW HYDROGRAPH IS
   5.00   6.40   8.40   9.64 10.00
INFLOW HYDROGRAPH IS LOGPEARSON T

   SLOPE=   0.2100000E-03 = 10.50

   TIME= 1.00
          VALUES OF THE VARIABL
DISTANCE   DEPTH   DISCHARGE
   0.0   5.70   13.948
   2.0   5.55   13.207
   4.0   5.44   12.627
   6.0   5.34   12.171
   8.0   5.27   11.821
  10.0   5.21   11.544
  12.0   5.17   11.329
  14.0   5.13   11.180
  16.0   5.10   11.029
  18.0   5.08   10.926
  20.0   5.06   10.847
  22.0   5.05   10.785
  24.0   5.04   10.738
  26.0   5.03   10.702
  28.0   5.02   10.679
  30.0   5.00   10.670